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STRUCTURAL RELATIONSHIPS OF TUFF-BRECCIA IN ABSAROKA RANGE, WYOMING

By Richard L. Hay

Abstract

Andesitic tuff-breccia showing unusual structural relationships is exposed throughout at least 100 square miles within two river valleys in the Absaroka Range of northwest Wyoming, a dissected mass of essentially horizontal volcanic deposits. The tuff-breccia occurs as sheetlike bodies within an otherwise dominantly detrital volcanic sequence. At least one, and perhaps all, of these sheets merges with thick masses of pyroclastic material. They display both intrusive and apparently gradational relationships to the detrital beds.

The tuff-breccia has the composition of pyroxene andesite but contains much foreign material, largely blocks of dacitic detrital volcanic rock, some of which are probably several miles from their source. Pronounced hardening (silicification ?) and greenish-gray coloration characterize dacitic detrital rock adjacent to the tuff-breccia.

Most of the tuff-breccia was probably erupted from a northwest-trending series of large vents. The structural relationships can be best explained by post-depositional movement of several sheets of tuff-breccia originally deposited at the surface and buried by detrital sediments. The tuff-breccia seems to have been injected as mud at relatively shallow depth into the detrital sequence, which was poorly consolidated.

How this post-depositional emplacement took place is not determined. Neither primary injection nor tectonic activity alone seems adequate to explain the unusual structural relationships; more probably, gravity was the main control, possibly aided by local doming.

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Introduction

General

The Yellowstone Park-Absaroka volcanic field has interested geologists since the early days of exploration in the West. The present study is concerned with andesitic tuff-breccia showing unusual structural relationships in two river valleys in the east-central part of the Absaroka Range—a rugged, dissected ac-

cumulation of essentially horizontal volcanic deposits bordering Yellowstone Park on the east and southeast (Fig. 1).

FIGURE 1.—INDEX MAP OF WYOMING

The study is based almost entirely upon data gathered during stratigraphic investigations, and is not intended to be a complete analysis of the problem. It is intended rather to point out the more prominent features of the tuff-breccia in the hope of stimulating further interest.

Nomenclature

The terminology used for the pyroclastic rocks is that proposed by Wentworth and Williams (1932):

(1) Tuff: "Indurated pyroclastic rocks of grain size generally finer than 4 mm; *i.e.* the indurated equivalent of volcanic ash or dust" (p. 50).

(2) Breccia: "More or less indurated pyroclastic rocks consisting chiefly of angular ejecta 32 mm or more in diameter. If the fine tuff matrix be abundant, the term tuff-breccia seems appropriate" (p. 46). Fifty per cent will be considered an abundant proportion of tuff matrix.

The terminology for the detrital volcanic rocks in this area has been discussed (Hay, 1952). These detrital rocks consist largely of volcanic detritus—of sand, silt, and pebble sizes—transported by streams and deposited in streams channels and flood plains. Water transportation was the controlling factor in determining the lithology, rather than subaerial deposition by ash falls. Some earlier writers have termed the finer-grained detrital rock "tuff," a term strictly applicable only to pyroclastic rock. Pyroclastic has been defined as "...an adjective commonly applied to rocks produced by explosive or aerial ejection of material from a volcanic vent" (Wentworth and Williams, 1932, p. 24). For these detrital rocks the writer believes it less ambiguous to prefix the adjective volcanic (*e.g.*, volcanic sandstone) to the terms used in the standard grade scale of Wentworth (1922, p. 381). Wentworth and Williams give tacit consent

to this nomenclature, for the term volcanic conglomerate is included (perhaps inconsistently) within their classification of pyroclastic rocks.

Stratigraphic Setting

The volcanic sequence in the northern and central parts of the Absaroka Range has been subdivided into six stratigraphic units (Hague, 1898). These are from oldest to youngest Early Acid Breccia, Early Basic Breccia, Early Basalt Sheets, Late Acid Breccia, Late Basic Breccia, and Late Basalt Sheets.

The tuff-breccia and related rocks are part of the Early Basic Breccia, which according to the mapping of Hague (1898) and to recent stratigraphic studies (Hay, 1952, unpub. thesis, Princeton Univ.) is the lowermost volcanic unit in the east-central part of the Absaroka Range. The Early Basic Breccia overlies the Early Eocene Willwood formation throughout most of the area, although locally it is underlain by Mesozoic strata and by blocks of Paleozoic limestone as much as 4 miles in diameter. Both vertebrate and plant fossils seem to indicate a Middle Eocene age for the Early Basic Breccia (paleontologic data summarized in Hay, 1952, unpub. thesis, Princeton Univ.).

The Early Basic Breccia comprises both a pyroclastic and a detrital facies and a number of lithologic types. The pyroclastic facies consists largely of unstratified, massive pyroxene andesite tuff-breccia, which is typically basic within the petrologic scale adopted for this volcanic province (Hague, 1896; 1898). The detrital facies consists of two subfacies, one characterized by andesitic (*i.e.*, basic) debris and the other by dacitic (*i.e.* acid) and a rather high percentage of nonvolcanic detritus. Volcanic sandstone is the predominant detrital type, but there are many conglomerates and siltstones. Claystone occurs in the lower part of the dacitic subfacies, and several tuff beds have been found in both dacitic and andesitic detrital subfacies.

The lithology of the Early Basic Breccia varies strikingly throughout the area (Fig. 2). In the northeast part of the area, this unit consists of coarse pyroclastic rock, whereas in the southwest part it comprises a detrital sequence overlain by tuff-breccia. In the central part it consists of interfingering detrital and pyroclastic deposits. The interfingering tuff-breccia displays cross-cutting contacts and other evidence of intrusive emplacement, indicating a complexity greater than that of simple intertonguing of facies.

The name "Early Basic Breccia" is not uniformly applicable to the rocks within this stratigraphic subdivision; much of the sequence is dacitic and nonpyroclastic. Names expressing neither composition nor texture should be used for this heterogeneous unit, but the problem of nomenclature is beyond the scope of the present study, and the current inappropriate terminology will be continued.

Acknowledgements

Field work, conducted during the summers of 1950 and 1951, was made possible by financial aid from Princeton University; faculty members of the geology department aided in the study. Prof. Hisashi Kuno, visiting fellow from Tokyo University, was of assistance in petrographic aspects of the problem, and Dr. W. G. Pierce, of the U. S. Geological Survey, contributed additional field data. Prof. Howel Williams, Dr. T. P. Thayer, and Dr. C. A. Anderson gave helpful criticism of the manuscript. I also wish to acknowledge the generous hospitality of Mrs. Eugene Phelps of Pitchfork, Wyoming.

Distribution of Tuff-Breccia

General

The tuff-breccia was studied on the northwest side of the valley of the South Fork of the Shoshone River (hereafter termed the "South Fork Valley") and on the northwest side of Greybull Valley. A smaller area of somewhat similar, though less well exposed tuff-breccia outcrops on the southeast side of the South Fork Valley, but no field study was made there. The tuff-breccia is particularly well exposed along the northwest side of South Fork Valley, where it is accessible by a good road from Cody (Fig. 2).

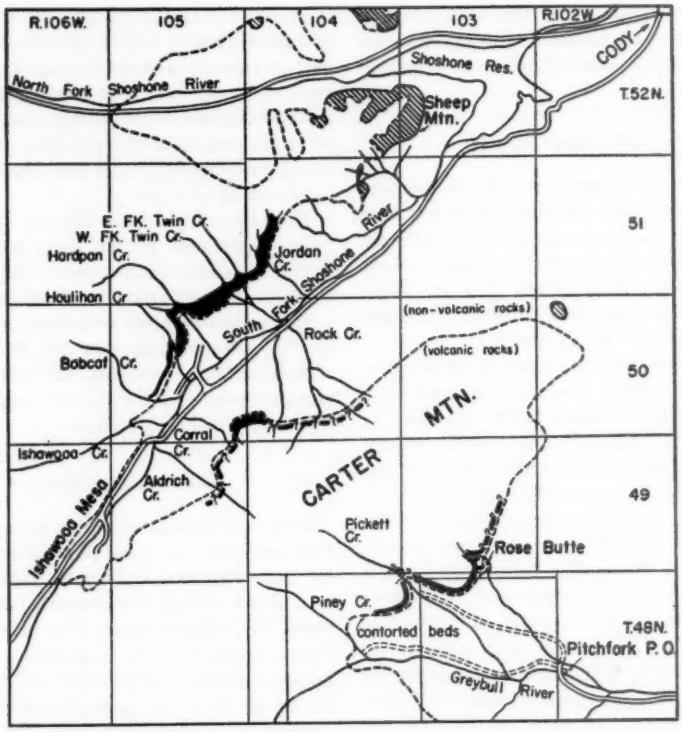

FIGURE 2.—MAP SHOWING OUTCROP AREAS OF TUFF-BRECCIA DISPLAYING UNUSUAL STRUCTURAL RELATIONSHIPS

Area indicated by small square in Fig. 1. Width of exposures of tuff-breccia displaying unusual structural relationships (termed "intrusive" tuff-breccia) somewhat exaggerated.

South Fork Valley

The tuff-breccia gross relationship is that of interfingering pyroclastic and detrital rock. At the northern end of the valley, the Early Basic Breccia is a rudely stratified, coarse pyroclastic pile. Thickness is unknown, because the top is eroded, but several miles to the north it is estimated to be 2000–3000 feet. The pyroclastic deposits divide into two members toward the southwest (Fig. 3). One member, about 500–1000 feet thick, overlies beds of the detrital facies; the other is intercalated as a tongue or sheet within the detrital sequence, extending from Jordan Creek southwest to within half a mile of Bobcat Creek, a total distance of about 8 miles. Southwestward, the sheet appears to end in landslide debris on the northeast side of the creek. The upper pyroclastic member is exposed about 12 miles farther southwest. Where both detrital and pyroclastic facies are present, the Early Basic Breccia is about 1500–2000 feet thick (Rouse, 1935; Hay, 1952, unpub. thesis, Princeton Univ.).

The sheet of tuff-breccia within the dominantly detrital sequence generally lies about

150 feet above the base of the Early Basic Breccia. Most commonly it ranges from 50 to 200 feet thick in the southwestern 3 miles to an estimated 350–400 feet toward the northeast; it appears to thin to 5 or 10 feet in a poorly exposed area between Houlihan and Hardpan creeks.

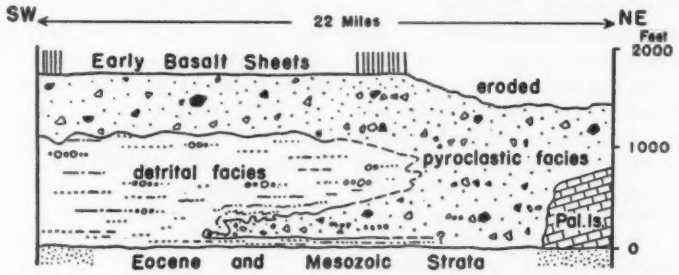

FIGURE 3.—DIAGRAM SHOWING GENERAL RELATIONSHIP OF PYROCLASTIC TO DETRITAL FACIES OF EARLY BASIC BRECCIA IN SOUTH FORK VALLEY

Cross section generalized from exposures along northwest side of South Fork Valley. Thicknesses approximate, faults not indicated.

The basal 350–400 feet of the detrital facies, excluding the sheet, consists largely of dacitic volcanic sandstone, siltstone, conglomerate, and claystone. Twenty-five feet of andesitic volcanic sandstone does, however, lie under the sheet in the northeast end of the cliff southwest of Hardpan Creek. About the same thickness of andesitic volcanic sandstone or tuff beds is exposed 50 feet above the tuff-breccia on the northeast side of Hardpan Creek (Pl. 2, fig. 2). The basal dacitic sequence probably intergrades or interfingers with andesitic detrital beds (the "Early Basic Tuffs" of Rouse, 1935, p. 276) along the southeast side of Ishawooa Mesa (Fig. 2), according to the work of Bruce Macomber (1952, unpub. thesis, Princeton University).

Greybull Valley

Several pyroclastic sheets interfinger with detrital beds in Greybull Valley (Fig. 2). One sheet extends southwest about 6 miles from Rose Butte, terminating in extremely contorted basic beds (Pl. 1). The northeastern extent of these sheets is unknown, but they may merge with the thick mass of pyroclastic rock forming the entire Early Basic Breccia where well exposed about 6 miles northeast of Rose Butte, at the northeast end of Carter Mountain. A thick, pyroclastic unit overlying the detrital facies as in South Fork Valley is absent here, although 100–200 feet of tuff-breccia is locally found at the top of the Early Basic Breccia. Over most of the area studied in Greybull Valley, the Early Basic Breccia is 1100–1400 feet thick; locally it is much thinner, and at one place (center N½ sec. 9, T. 48 N., R. 104 W.) it is only about 200 feet thick.

The tuff-breccia intercalated within the detrital sequence does not form a single, well-defined sheet but occurs as two or three sheets which appear connected in several places. Individual sheets range from 80 to 350 feet in thickness. The maximum thickness of this tuff-breccia in any measured section is about 500 feet.

The detrital facies is more complex on the northwest side of Greybull Valley than in South Fork Valley. Dacitic beds form several 20- to 100-foot units at different horizons rather than a basal 350- to 400-foot sequence. The thickest dacitic unit appears to be persistent, however, and throughout most of this area lies 600–700 feet above the base of the Early Basic Breccia. Both dacitic and andesitic detrital beds show greater lithologic variation here than in South Fork Valley.

STRUCTURAL RELATIONSHIPS OF TUFF-BRECCIA

Conformable Contacts

In several places the sheets of tuff-breccia are conformable both to underlying and overlying beds. Tuff-breccia, 50–75 feet thick, is conformably intercalated within the dacitic

sequence on the northeast side of Houlihan Creek (Pl. 2, fig. 1), and a sheet of coarse tuff-breccia, 80 feet thick, appears to be conformably underlain and overlain by detrital volcanic beds in Greybull Valley at or near the NW corner sec. 5, T. 48 N., R. 103 W.

Tuff-breccia grades into stratified, rather well-sorted beds at several places. Such gradation can be seen above the cliff a third of a mile southwest of Rose Butte, where tuff-breccia grades upward into a 150-foot sequence of andesitic tuff (possibly volcanic sandstone and siltstone) and breccia beds. This stratified sequence in turn grades upward into an estimated 100–150 feet of tuff-breccia. Unstratified tuff-breccia appears to grade downward into a stratified, conglomeratic facies of the sheet on both sides of the East Fork of Twin Creek, in South Fork Valley. Although the contact is partly obscured by talus, tuff-breccia interfingers and probably intergrades laterally with the extremely contorted beds in Greybull Valley (Pl. 1).

Truncation of Detrital Beds

An entire sheet of tuff-breccia cuts across detrital beds at a low angle about half a mile southwest of Houlihan Creek, in South Fork Valley. Here the upper surface of the sheet cuts across successively higher beds toward the southwest. The lower surface of the sheet also truncates the sequence, as indicated by volcanic sandstone below the sheet which very probably represents the beds that overlie the sheet about 250 feet to the northeast.

Truncation can be observed on a smaller scale at a number of places. The upper surface of the southwest part of the sheet in the South Fork Valley is irregular, and detrital beds are truncated by these irregularities. A crosscutting apophysis is visible in the cliff southwest of Hardpan Creek, and an oval-shaped exposure of tuff-breccia above the same cliff may be the eroded cross section of an offshoot extending upward from the sheet. Tuff-breccia cuts across horizontal andesitic conglomerate beds, about 150 feet thick, with a near-vertical contact at Rose Butte (Fig. 4). The basal surface of a sheet in Greybull Valley apparently truncates detrital beds at one place (Fig. 2, E½ N¼ sec. 10, T. 48 N., R. 104 W.). Horizontal dacitic beds, 50–75 feet thick, and predominantly non-volcanic, underlie the tuff-breccia and terminate laterally against it. The tuff-breccia either channeled into these horizontal beds or filled a channel cut into them.

Deformation of Detrital Beds

Detrital beds adjacent to the tuff-breccia are locally folded, faulted, and brecciated. Elsewhere at several places detrital beds have been deformed in a more unusual manner.

Folded and even intensely contorted detrital beds overlie tuff-breccia at a number of places. Folding is well illustrated by a synclinal block of coarse andesitic conglomerate underlain by tuff-breccia about half a mile southwest of Rose Butte. This block measures several hundred feet in width, plunges about 45° S., and its limbs dip 30°–40°. Similar andesitic conglomerate beds overlying tuff-breccia on Rose Butte have dips of about 30°–50°, but the attitude of these beds may reflect deformation related to the vent filling of olivine-augite andesite rather than to the tuff-breccia (Fig. 4). Contortion of overlying beds is most evident in South Fork Valley, particularly above thickened parts of the sheet. Intensely contorted beds can be seen above the thick mass of tuff-breccia northeast of Houlihan Creek (Pl. 2, fig. 1).

Faulting of detrital beds adjacent to tuff-

PLATE 1.—INCLUDED BLOCKS OF VOLCANIC SANDSTONE AND EXTREMELY CONTORTED BEDS IN GREYBULL VALLEY

FIGURE 1.—INCLUDED BLOCKS OF VOLCANIC SANDSTONE

Blocks (A_1, A_2) consist largely of dacitic volcanic sandstone; they are engulfed in tuff-breccia (T) and andesitic beds (C) which form part of extremely contorted mass at right side of Plate 1, figure 2. Bedding of larger block (A_2) in part vertical (v), in part nearly horizontal but overturned (o). Arrows indicate undisturbed dacitic volcanic sandstone beds underlying tuff-breccia and larger block. Part of block A_2 shown about 600 feet long from left to right.

FIGURE 2.—EXTREMELY CONTORTED BEDS

These form uppermost 350–400 feet of Early Basic Breccia at one place (N½ sec. 10, T. 48 N., R. 104 W.) in Greybull Valley. Lava flows (L) of Early Basalt Sheets overlie contorted beds. Evenly-stratified beds above lava flows represent Late Basic Breccia.

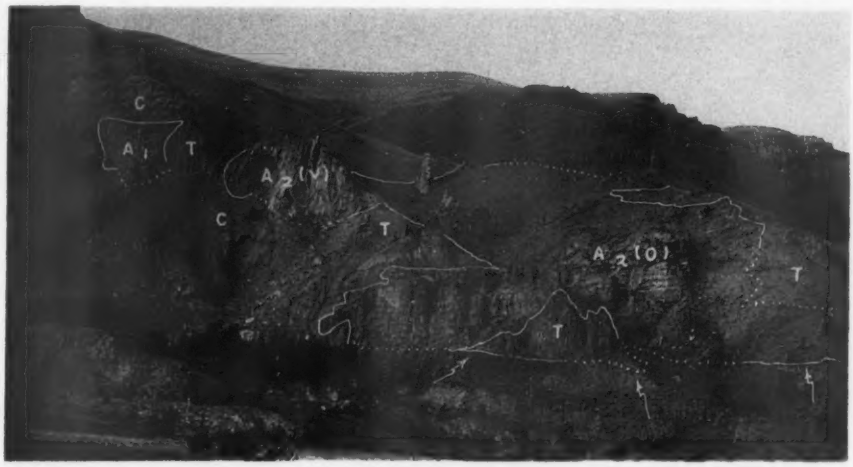

FIGURE 1

FIGURE 2

INCLUDED BLOCKS OF VOLCANIC SANDSTONE AND EXTREMELY CONTORTED BEDS IN GREYBULL VALLEY

FIGURE 1

FIGURE 2

TUFF-BRECCIA EXPOSED IN SOUTH FORK VALLEY

breccia is evident northeast of Houlihan Creek (Pl. 2, fig. 1); here a massive 40-foot conglomeratic volcanic sandstone bed is cut by two topmost is bent upward nearly vertically as though it were being torn from the detrital sequence.

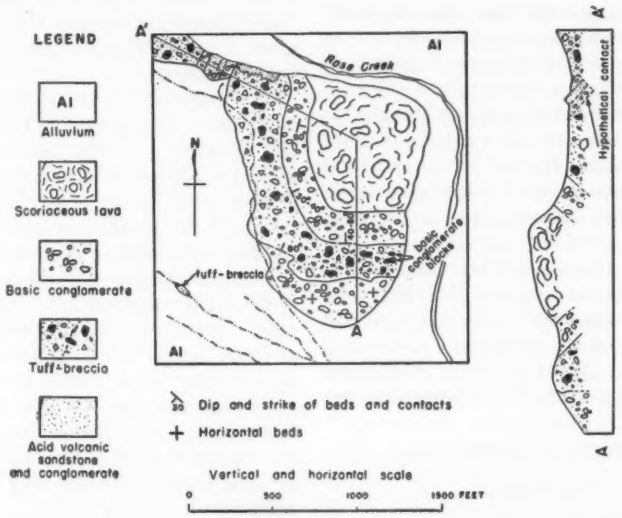

FIGURE 4.—GEOLOGIC MAP AND CROSS SECTION OF ROSE BUTTE IN GREYBULL VALLEY
Distances approximate, estimated by eye only.

reverse faults, each of 50-foot displacement, with the direction of thrust away from the mass of tuff-breccia.

Minor brecciation of detrital rock was observed at the base of the cliff southwest of Hardpan Creek. Here the bedding of a 25-foot layer of andesitic volcanic sandstone underlying tuff-breccia is offset by many fractures having displacements of several inches.

Deformation of a different nature is indicated by exposures at the base of the cliff a third of a mile southwest of Rose Butte. Here, conglomeratic andesitic volcanic sandstone, 25–50 feet thick, underlies 300–350 feet of tuff-breccia. Most of the detrital beds are horizontal, but the

Unusual deformation is also displayed by the 150-foot sequence of andesitic tuff and breccia between two sheets of tuff-breccia a third of a mile southwest of Rose Butte. The finer-grained beds are penetrated by a number of breccia pipes and very irregular intrusive masses from 1 to 4 feet in diameter and as much as 10 feet long. The intrusions terminate upward within the bedded sequence; none extends downward into the underlying tuff-breccia. The breccia of these small intrusive masses is similar to that of the breccia beds within the stratified unit and was almost certainly derived from them, probably by squeezing or other deformation while the beds were still unconsolidated.

PLATE 2.—TUFF-BRECCIA EXPOSED IN SOUTH FORK VALLEY

FIGURE 1.—TUFF-BRECCIA NORTHEAST OF HOULIHAN CREEK

Complex relationships northeast of Houlihan Creek. Part of sheet exposed at left (D), 50–75 feet thick, conformably intercalated between detrital beds. Large mass at right, about 200 feet thick, displays discordant relationships to adjacent beds, which are truncated, and to some overlying beds (B), which are contorted. Thrust-fault (C) cuts massive volcanic sandstone bed. (A) indicates andesitic tuff which occurs above typical tuff-breccia.

FIGURE 2.—TUFF-BRECCIA AND LARGE SLUMPED BLOCK NORTHEAST OF HARDPAN CREEK

Large block of dacitic volcanic sandstone and siltstone (B) has slumped down into tuff-breccia (T). Block unconformably overlain by andesitic tuff or volcanic sandstone beds (arrow). Block about 500 feet long from left to right.

Engulfment of Large Detrital Blocks

Many blocks from the detrital facies are enveloped by the tuff-breccia. Slumping of overlying beds into the tuff-breccia is particularly well illustrated by the large block exposed on the northeast side of Hardpan Creek (Pl. 2, fig. 2). This block is estimated to be 500 feet long and 200 feet thick and lithologically resembles the beds normally overlying the tuff-breccia in this area. The largest block of detrital volcanic rock engulfed in tuff-breccia lies in Greybull Valley between Piney and Pickett creeks (Fig. 2, E½ N¼ sec. 10, T. 48 N., R. 104 W.). This irregular and contorted block of volcanic sandstone is about 750 feet long; most of it is upside-down, but some is vertical (Pl. 1, fig. 1). Though apparently a single block, this mass may consist of two or more blocks lying in contact and having different attitudes.

Lithologic Description

Tuff-Breccia

Most of the tuff-breccia is well indurated, massive, and unstratified, although a stratified, conglomeratic facies forms much of the northeastern 4 miles of the sheet in South Fork Valley. The tuff-breccia consists chiefly of tuff matrix and angular to moderately well rounded (generally subangular), nonvesicular fragments of pyroxene andesite. The coarse fragments range from lapilli size (4 mm) to as much as 5 feet in diameter. The fresh surface is light olive gray to pale yellowish brown (Rock Color Chart Committee, 1948); the weathered surface is light olive gray to moderate yellowish brown. The tuff-breccia commonly weathers into prominently castallated escarpments.

The content of coarse fragments is variable in both South Fork and Greybull valleys. Tuff matrix forms about three-fourths of the most widely distributed tuff-breccia, in which relatively few coarse fragments exceed 12 inches in diameter. Coarser tuff-breccia containing 40–50 per cent of fragments, many 1–3 feet in diameter, forms much of the northeast 4 miles of the sheet in the South Fork Valley and is prominent on the northwest side of Greybull Valley. A few local concentrations of breccia were found in the finer-grained tuff-breccia in the area of Hardpan Creek, both as pockets 5–10 feet in diameter and as bands 1–2 feet thick. Tuff-breccia containing relatively few coarse fragments (perhaps more properly "tuff") forms the uppermost 5–15 feet of the sheet at several places in South Fork Valley (*e.g.*, Pl. 2, fig. 1).

The conglomeratic facies, well exposed on both sides of the East Fork of Twin Creek, consists of crudely to rather well-stratified, subangular to subrounded debris, composed chiefly of pebbles and cobbles in a volcanic sandstone matrix. A few boulders as much as 2 feet in diameter were found in this conglomerate.

Field and laboratory study indicate that most of the coarse fragments in the tuff-breccia are either pyroxene andesite or hornblende-augite andesite. Augite and hornblende phenocrysts are generally visible, and in two thin sections the groundmass mafic minerals are augite and hypersthene. The plagioclase of one nonporphyritic specimen is An_{40}. The volume of mafic minerals suggests that the rock is a medium andesite.

The tuff matrix is clearly fragmental and also probably andesitic. It consists largely of rock fragments, crystal fragments, and material too fine to identify. Most of the rock fragments consist of plagioclase and augite crystals in a groundmass of dark-brown or black glass. Finely crystalline, pyroxene andesite fragments are also common. Small pseudomorphs after olivine and hypersthene are visible in some of the rock fragments. Most of the plagioclase in the tuff matrix is between An_{38} and An_{45}. A heavy-liquid separate of one specimen contains chiefly augite, oxyhornblende, and green-brown hornblende. The absence of hypersthene in the heavy-liquid separate is not surprising, as unaltered hypersthene is absent from all the Early Basic Breccia studied, except for some of the larger rock fragments. This absence is probably due to destruction during and after deposition (Hay, 1952, unpub. thesis, Princeton Univ.).

Foreign Material

Foreign material is common in much of the tuff-breccia. Included blocks of detrital volcanic rock are the most abundant type of such

material; these would probably be termed accidental by Wentworth and Williams (1932). Quartzite cobbles and blocks of pyroclastic rock and Paleozoic limestone have also been found in the tuff-breccia. This foreign material is most abundant in the finer-grained tuff-breccia; it is relatively rare in the coarser and in the conglomeratic facies. Although commonly concentrated in the uppermost tuff-breccia, these blocks are intermixed throughout the sheets. Several blocks were also found in breccia beds in the uppermost part of the stratified basic sequence (underlain and overlain by tuff-breccia) a third of a mile southwest of Rose Butte.

Size and shape of the blocks vary greatly. The blocks range in length from less than 1 foot to as much as 750 feet; they are generally 6–8 feet long. A tabular shape is most common, but some are extremely irregular and deformed.

The contact of the tuff-breccia with many blocks is irregular. Some of the blocks are cut by dikes and dikelets of tuff-breccia; a few are penetrated by irregular stringers. Coarse basic fragments are concentrated on the surface of several included blocks, projecting as much as 2–3 inches into the inclusions.

The foreign material varies considerably in composition. Blocks of dacitic volcanic sandstone and conglomerate are most common, but andesitic volcanic sandstone and conglomerate blocks also are present. Some conglomerate blocks contain both dacite and andesite pebbles. A few basic tuff-breccia blocks, finer-grained than the enclosing tuff-breccia, have been found. There is also a small number of blocks consisting largely of well-rounded quartzite pebbles and cobbles but with an intermixture of volcanic hypabyssal, and plutonic pebbles. Volcanic pebbles of the latter blocks range in composition from dacite with many large quartz phenocrysts to olivine-rich basalt(?). Several Paleozoic limestone blocks, 1–5 feet in diameter, were found in talus at the foot of the sheet on both sides of the West Fork of Twin Creek, in South Fork Valley. Although not observed in place their concentration in the talus and the adherence of tuff-breccia to the surface of one block suggest that they were at one time enveloped by the tuff-breccia. Well-rounded quartzite cobbles most of which have diameters of 3–4 inches are sparsely but uniformly dispersed throughout the finer-grained tuff-breccia.

The bedding of many of the dacitic volcanic sandstone inclusions in the Greybull Valley is cut by dikelets of similar volcanic sandstone. These dikelets can be traced to beds within the inclusions, which were the source of the dike material. The largest dikelet observed, about 4 inches wide and 6 feet long, was found on the south side of the 750-foot block. At another place, the marginal 6 feet of this large block contain several greenish-gray, volcanic, siltstone blocks cut by irregular dikelets of volcanic sandstone from the large block.

Most of these included blocks are lithologically similar to near-by beds and were probably derived from them. Some blocks, however, lie several miles from similar beds, and at least one cannot be matched with any known bed.

One can see this resemblance to adjacent beds in many places. The blocks exposed in the cliff a third of a mile southwest of Rose Butte can be perfectly matched with the acid beds overlying the tuff-breccia and intergrading andesitic beds. Composition and texture of the detrital beds change rapidly here, and the lithologic similarity between blocks and beds suggests that the blocks were derived from the overlying beds in this vicinity. As has been mentioned, the large slumped block exposed on the northeast side of Hardpan Creek (Pl. 2, fig. 2) is similar to the beds which normally overlie the tuff-breccia in that area. Several blocks of coarse andesitic conglomerate on Rose Butte are enclosed within tuff-breccia about 200 feet laterally from the near-vertical contact with similar conglomerate beds (Fig. 4). Near the 750-foot block in the Greybull Valley, several conglomerate blocks, about 3 feet thick and consisting largely of quartzite pebbles and cobbles, lie about 350 feet above a similar bed, about 3 feet thick. This conglomerate bed is the only one of its kind observed in the vicinity; hence it was probably the source of the near-by conglomerate blocks. Presence of the conglomerate blocks in the tuff-breccia suggests that the tuff-breccia channeled into these beds rather than filled a pre-existing channel. A few irregularly shaped blocks of finer-grained tuff-breccia, containing smaller

blocks of dacitic volcanic sandstone, occur in coarse tuff-breccia about 150 feet stratigraphically above tuff-breccia similar to that of the blocks (Fig. 2, NW corner sec. 5, T. 48 N., R. 103 W.).

Many detrital volcanic blocks lie at least several miles from exposures of similar beds. For example, the 750-foot block in Greybull Valley is essentially similar, both in thickness and lithology, to a detrital sequence underlain and overlain by tuff-breccia about 1½ miles northeast, in the SW¼ sec. 1, T. 48 N., R. 104 W. (Fig. 2; Fig. 5, columnar sections 1 and 2). A block of coarse andesitic conglomerate was found near the SW corner of sec. 1, T. 48 N., R. 104 W. (Fig. 2), about 5 miles southwest of similar beds underlain and truncated by tuff-breccia at Rose Butte and in the cliff southwest of the butte. These, and other blocks unlike near-by beds may have been supplied from beds, now either unexposed or destroyed by erosion, that were nearer than the above-mentioned ones which lie 1½—5 miles from similar blocks. It is significant, however, that most of these blocks are similar to beds overlying tuff-breccia, occurring between two sheets of tuff-breccia, or truncated by tuff-breccia; many blocks are totally dissimilar to beds lying under the tuff-breccia, and have probably been supplied from relatively distant overlying beds.

The blocks of conglomerate consisting largely of quartzite pebbles and cobbles resemble only one known bed, and their source is more difficult to explain. One block was found in the cliff southwest of Rose Butte, about 5 miles east of the similar bed, which may possibly be the source of the block. Several blocks of similar conglomerate were found on both sides of Hardpan Creek, in South Fork Valley about 15 miles from the similar bed in Greybull Valley. One of these blocks is about 15 feet thick, however, and cannot properly be matched with the 3-foot bed in Greybull Valley. These conglomerate blocks are totally dissimilar to underlying beds in South Fork Valley, but pebbles and cobbles in the blocks are like those in some overlying beds. The stratigraphy in South Fork Valley is relatively uniform, and the blocks were very likely derived from an overlying bed probably a mile or more distant.

The quartzite cobbles scattered throughout the tuff-breccia are similar to those in a few beds of the detrital facies of the Early Basic Breccia, within some conglomerate blocks in the tuff-breccia, and in beds of the Willwood formation in this area. The quartzite cobbles are too well-rounded to have been shaped by such a volcanic mechanism as Farmin (1934, p. 367) has suggested to explain "pebble dikes". Evidence is insufficient, however, to determine the particular source of the cobbles.

The Paleozoic limestone blocks in South Fork Valley are similar to the limestone of Sheep Mountain and nearby large limestone blocks, about 7 miles northeast. Some of these large limestone blocks are cut by intrusive breccia bodies (Rouse, 1937, p. 1293; Pierce, 1938, p. 1896), and the smaller blocks in tuff-breccia may be fragments broken from the large blocks during intrusion.

Contact Alteration

Alteration consisting of pronounced hardening and greenish-gray coloration is characteristic of both dacitic detrital beds and the included blocks of these beds from 1 to 6 feet from the contact with tuff-breccia. No alteration of andesitic detrital beds or included blocks is apparent. Alteration of dacitic rock is not restricted to contact with tuff-breccia, however. The margin of the large dacitic block unconformably overlain by stratified andesitic tuff or volcanic sandstone northeast of Hardpan Creek (Pl. 2, fig. 2) is similarly altered.

Thin-section study shows no apparent mineralogic or textural differences between the altered and unaltered dacitic rock, although the matrix of the altered rock is somewhat darker. Hardening of the altered rock may be due to silicification, but no finely crystalline silica was visible under the microscope, and no chalcedony was found in the field.

Primary alteration due to heat and volatiles seems unlikely, for dacitic rock is altered at the contact with basic sedimentary beds as well as the tuff-breccia. Alteration may be due to differential ground-water solution and deposition of silica, and perhaps to other compounds or ions between the dacitic detrital rock (generally characterized by a high percentage of nonvolcanic detritus) and the andesitic rock

(almost entirely volcanic material). Consistent with this suggestion is the lack of similar alteration of andesitic detrital beds in contact with the tuff-breccia.

Nature of Emplacement

The distribution of the exposed areas of tuff-breccia having unusual structural relationships seems to indicate that at the time of emplacement they were connected sheetlike masses. The tuff-breccia is lithologically similar in South Fork and Greybull valleys and occurs at about the same stratigraphic horizon in both areas. Furthermore, structural relationships to adjacent beds are essentially similar in both river valleys. The present discontinuity between the outcrop areas on opposite sides of South Fork Valley is probably due to recent erosion by the South Fork of the Shoshone River; that between South Fork and Greybull valleys represents concealment by the stratigraphically higher rocks forming the upper part of Carter Mountain. If this inference is correct, then originally the sheets of tuff-breccia covered at least 100 square miles.

Intrusive relationships and included blocks from overlying beds clearly indicate that much of the tuff-breccia was emplaced after the overlying detrital beds had been deposited. Underground movement of at least 1–2 miles is probably necessary to account for observed relationships. The exposures southeast of Houlihan Creek, where the entire sheet cuts across beds about a mile from its southwest termination, suggest northeast to southwest-transport of about a mile. This evidence is not conclusive, however, for the truncated beds appear to be part of a down-dropped fault block; northwest to southeast injection from tuff-breccia conformably interbedded in the undisturbed block a short distance away must be considered a possibility. Movement of 2–3 miles, some of which was probably at or near the surface, is suggested by stratigraphic relationships in Greybull Valley (Fig. 5). Tuff-breccia underlies a 100-foot dacitic detrital unit northeast of Pickett Creek; 2½ miles southwest, equivalent detrital beds are both underlain and overlain by tuff-breccia containing large blocks of similar detrital rock. About 1½ miles farther southwest the 750-foot block, of similar lithology, is nearly enclosed in equivalent tuff-breccia. The tuff-breccia appears to have moved underground toward the southwest, cut across the dacitic beds, and deformed and transported a large block of dacitic sandstone.

The included blocks do not clearly indicate the maximum distance the tuff-breccia has moved underground. Many blocks of foreign material are unlike adjacent beds, but owing to possible facies changes, the source of blocks unlike adjacent beds in this area cannot be determined with accuracy. As many of these blocks are most similar to beds overlying tuff-breccia or interbedded between two sheets of tuff-breccia several miles distant it seems likely that some have been transported underground as much as a mile, and perhaps considerably more.

Intrusive relationships and foreign blocks are largely restricted to the finer-grained tuff-breccia, which moved farther than the coarser tuff-breccia and the conglomeratic facies of the sheet in South Fork Valley. The bedding of the conglomeratic facies is relatively undisturbed; this part of the sheet probably moved only a short distance, if at all. The Paleozoic limestone blocks in this coarser, conglomeratic facies of the sheet were probably derived from the large blocks directly underlying the pyroclastic facies of the Early Basic Breccia, hence they are not evidence for underground movement.

The large size and tabular shape of many of the included blocks of detrital volcanic rock, some of which were relatively unconsolidated at the time of engulfment in the tuff-breccia, strongly suggest "nondisruptive" emplacement of the tuff-breccia (*i.e.*, relatively quiet movement as contrasted with violent emplacement by a volcanic explosion). Mud flow is an important mode of tuff-breccia emplacement (Anderson, 1933, p. 252–261), and Rouse has pointed out that abundant moisture for the development of mud flows was present in the Absaroka volcanic field (1937, p. 1281). Mud flow during deposition of the Early Basic Breccia is almost certainly indicated by the observed contortion in Greybull Valley (Pl. 1, fig. 2) and elsewhere in this part of the Absaroka Range, and tuff-breccia interfingers and prob-

ably intergrades with such contorted beds at one place (Pl. 1, fig. 1).

The thickness of beds overlying the tuff-breccia at the time of mud flow was probably not great; locally movement took place at or near the surface. Detrital beds, normally about 400 feet above the tuff-breccia, are truncated by the sheet southwest of Houlihan Creek, thus indicating a minimum thickness of the overlying sequence here. The beds overlying the large, slumped block northeast of Hardpan Creek (Pl. 2, fig. 2) are similar to some within the upper part of the detrital facies of the Early Basic Breccia; thus, slumping occurred during deposition of the detrital rocks. When slumping occurred the maximum possible thickness of detrital beds overlying the sheet in this area is estimated to have been about 1000 feet, and was probably much less. The tuff-breccia was probably emplaced at or near the surface in Greybull Valley, for tuff-breccia is now exposed about 100 feet below the top of the Early Basic Breccia in one place (Pl. 1, fig. 1), and contorted beds interfingering with tuff-breccia lie directly under the Early Basalt Sheets in the same area (Pl. 1, fig. 2).

Several features indicate that the tuff-breccia was forcefully injected, at least locally. This is most strongly suggested by the exposures on the northeast side of Hardpan Creek (Pl. 2, fig. 1). Here a thick portion of the sheet has truncated an estimated 150 feet of beds laterally adjacent. A massive 40-foot bed of sandstone in this sequence is cut by two 50-foot reverse faults, with the direction of thrust away from the tuff-breccia. Beds lying above the edge of this tuff-breccia mass are domed. The near-by continuation of the tuff-breccia sheet southwest of the large mass is only 5–10 feet thick, as if compression of beds adjacent to the mass during injection has squeezed most of the tuff-breccia out of the sheet here. Crosscutting of detrital beds by the sheet southwest of Hardpan Creek also suggests forceful injection, for crosscutting must have required considerable force, if only to raise the overlying beds during penetration along a pre-existing fault plane. Deformation and overturning of the 750-foot

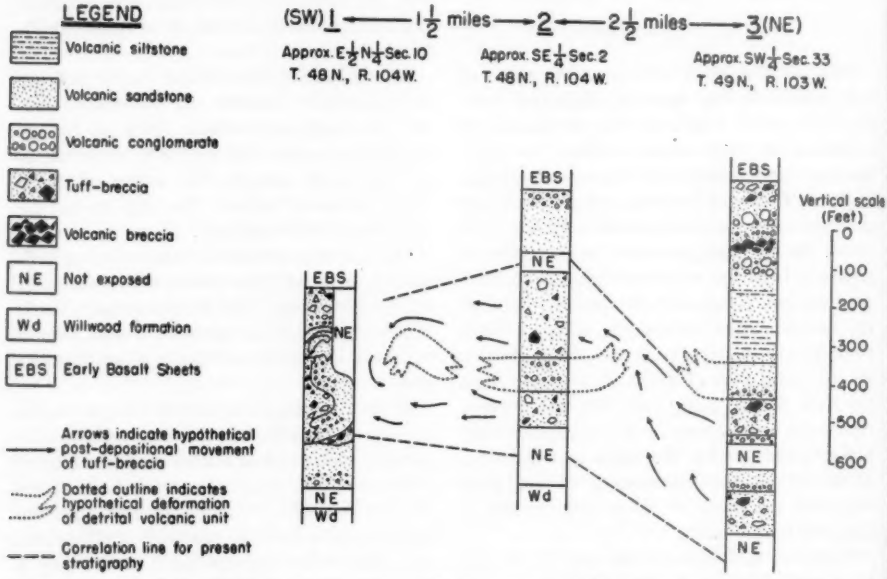

FIGURE 5.—DIAGRAM SHOWING HYPOTHETICAL EXPLANATION OF STRATIGRAPHIC RELATIONSHIPS IN THREE COLUMNAR SECTIONS ON NORTH SIDE OF GREYBULL VALLEY

Detrital block in columnar section 1 represents one in this area about 750 feet long.

block in Greybull Valley must have required considerable force.

The direction of underground mud flow can be roughly inferred from the apparent direction of injection. The direction of thrusting of detrital beds in South Fork Valley suggests movement from northeast to southwest. This evidence for movement from the northeast may be apparent rather than absolute, however, for the orientation of exposures may be misread; movement from the north or east might also have produced the observed features. The interpretation of stratigraphic relationships in the west end of Greybull Valley accepted here (Fig. 5) indicates northeast to southwest movement.

The detrital beds were probably unconsolidated during final emplacement of the tuff-breccia. The extreme contortion of basic beds with which tuff-breccia interfingers and probably intergrades (Pl. 1, fig. 2) is not accompanied by significant fracturing; hence contortion must have occurred while the beds were plastic. The small "intraformational" breccia intrusions in the stratified sequence intergrading upward and downward with tuff-breccia also suggest deformation of relatively unconsolidated material. Poor consolidation is suggested by the contortion of some of the detrital blocks in the tuff-breccia and by the volcanic sandstone dikelets within these blocks. Particularly striking is the engulfment of siltstone inclusions within the marginal 6 feet of the 750-foot dacitic block, for this certainly implies that the latter was then plastic.

The emplacement of the tuff-breccia thus seems to have been rather unusual; mud was forcefully injected at shallow depth into poorly consolidated beds. The detrital beds were deformed; blocks of these beds became enveloped by tuff-breccia and were probably transported as much as a mile or more. Some of the detrital beds were completely disrupted, and in at least one place tuff-breccia mud reached the surface.

Source of Tuff-Breccia

Volcanic vents were the source of the pyroclastic facies of the Early Basic Breccia in the Absaroka Range (Rouse, 1937, p. 1273–1280), and W. G. Pierce has found evidence for a northwest-trending series of intrusive breccia bodies exposed at the southwest end of Sheep Mountain, where "there are fissures or linear types of intrusions half a mile or more in width" (Pierce, 1953, personal communication). The sheet of tuff-breccia in South Fork Valley merges with the breccia of the intrusive bodies; eruption of the sheet from these vents seems almost certain. The unstratified, chaotic appearance of the pyroclastic rock exposed at the northeast corner of Carter Mountain suggests a large local vent belonging to the northwest-trending series, with which the tuff-breccia sheets in Greybull Valley may similarly merge. The apparent northeast to southwest injection of the tuff-breccia supports the evidence which suggests that the tuff-breccia in both valleys originated from the northwest-trending series of vents.

A dike of tuff-breccia occurs in Greybull Valley southwest of the zone of intrusive breccias. It lies in the NW¼ sec. 5, T. 48 N., R. 103 W. (Fig. 2) and measures 1000–1500 feet long and about 150 feet wide. Although lithologically similar to a near-by sheet of coarse tuff-breccia, it cuts beds 100–200 feet stratigraphically higher, and it is apparently younger than the sheet. The lithologic similarity suggests a genetic relationship, and the dike may be an offshoot of the sheet. Local vents in this area are perhaps suggested, however, by differing lithologies of the sheets of tuff-breccia in Greybull Valley.

Mechanism of Emplacement

Primary Injection

The intrusive features and continuity of at least one of the sheets with large intrusive breccia bodies suggests that the sheets were laccolithic injections. Subcrustal formation of tuff-breccia, resembling that of the Absaroka Range, and its eruption to form surface mud flows is a geological phenomenon which is becoming more widely recognized (especially Durrell, 1944, p. 267–272). Primary lateral injection of such material has not been reported, however, and the occurrence of a local conglomeratic facies in one sheet and the intergradation of tuff-breccia with well-stratified

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and rather well-sorted sedimentary beds is difficult to explain by this mechanism. Furthermore, injection at shallow depth into poorly consolidated beds would almost certainly have resulted in surface discharge rather than intrusion of connected sheets having a probable surface area of at least 100 square miles.

Tectonic Emplacement

There was considerable tectonic activity during the accumulation of the Absaroka volcanic sequence; hence the possibility of tectonic emplacement of the tuff-breccia should be examined.

Faults, both normal and reverse, having displacements of 50–200 feet, cut beds of the detrital facies at a number of places in South Fork Valley (Macomber, 1952, unpub. thesis, Princeton Univ.). No similar faults were seen cutting either the overlying or intercalated tuff-breccia, so the faulting probably took place during deposition of the Early Basic Breccia, perhaps just prior to or during injection of the tuff-breccia. Some of these faults may be a result of the tuff-breccia injection, but movement along these faults could not very well have caused the injection. Emplacement of the sheet as a whole by squeezing of the interfingering tuff-breccia along a flat-lying fault plane is unlikely, for no such fault was found, and the relatively thin cover of poorly consolidated beds overlying the tuff-breccia was not rigid enough to transmit tectonic forces over the distance required.

Doming was an important tectonic process in the Absaroka Range. Regional doming to the north of the area may have occurred prior to or during emplacement of the large limestone blocks underlying the Early Basic Breccia in this area (Bucher, 1947, p. 193) and after deposition of the Early Basalt Sheets (Rouse, 1937, p. 1291). Similar doming during deposition of the Early Basic Breccia is suggested by the presence of an angular unconformity within this stratigraphic unit on the southeast side of Ishawooa Mesa (Fig. 2). The angular unconformity between tuff-breccia and detrital beds is locally as much as 10°, and the tuff-breccia fills valleys as much as 200 feet deep. Thinning of the Early Basic Breccia to about 200 feet at one place suggests local doming in Greybull Valley; the usual thickness in this area is 1100–1400 feet. A genetic relationship of this local doming in Greybull Valley to mud flow seems likely, as the beds on the flank of the probable dome are intensely contorted (Pl. 1, fig. 2). The inferred dome occurs in the wrong location to have been the cause of northeast to southwest injection in this area; however, there may be a less direct relationship.

A synclinal flexure in the Early Basalt sheets overlies the axis of the probable dome in Greybull Valley. This syncline may represent subsidence following doming, but more data are necessary to substantiate this suggestion.

The large Paleozoic limestone blocks underlying the Early Basic Breccia in South Fork and North Fork valleys indicate unusual tectonic activity; a genetic relationship to the unusual structural relationships of the tuff-breccia might be expected. Pierce (1941, p. 2026, 2033; 1950, p. 1493) and others have suggested that these blocks are remnants of a once-continuous limestone sheet. Bucher, however, has expressed the opinion that the blocks ". . . do not represent remnants of a once-continuous 'thrust-sheet', but came into existence as independent fragments" (1947, p. 194). Similarly, diverse opinions have been held concerning the emplacement of these limestone blocks. Pierce (1941) and others advocated tectonic emplacement as the "Heart Mountain Overthrust"; Bucher suggested that the blocks ". . . were thrust eastward and scattered much as they exist today by the horizontal component of the force of a large volcanic explosion" (1933, p. 239). Later both Bucher (1947, p. 196) and Pierce (1950, p. 1493) accepted gravity as the dominant propelling force.

These limestone blocks underlie the Early Basic Breccia and are cut by intrusive breccia bodies (Rouse, 1937, p. 1293; Pierce, 1938, p. 1896); they were emplaced prior to or during the earliest eruptions of the Early Basic Breccia in this area and are probably related only indirectly, if at all, to the sheet of tuff-breccia in this area.

In summary, doming may have been a factor in the final emplacement of the tuff-breccia, but no more direct tectonic control, such as near-surface thrusting, is apparent.

Gravity Emplacement

The probable gravity emplacement of a widespread limestone sheet or a number of large limestone blocks in this area focusses attention upon the importance of gravity as a geologic agent in the Absaroka Range. Contortion of sedimentary beds in Greybull Valley and elsewhere in this part of the Absaroka Range is probably evidence of the effect of gravity upon unconsolidated rocks; the intrusive relationships of the tuff-breccia can possibly be explained as a result of post-depositional gravity adjustment of lenticular sheets originally deposited at the surface and buried by detrital beds. Lateral injection might have been caused by greater density and mobility of the tuff-breccia on a gradient locally increased by doming. The relatively slight difference in density (estimated to be 0.2–0.4) between the tuff-breccia and dacitic detrital rock, and the rather low gradient apparent from present exposures seem, however, inadequate to account for forceful injection, particularly of a mile or more.

To the northeast, the Early Basic Breccia is almost entirely pyroclastic; to the southwest, it is largely detrital. Injection of the sheets of tuff-breccia may therefore represent gravitational adjustment between the two facies. Movement of 1–2 miles might not have been excessively great in terms of the total masses involved. The pyroclastic facies northeast of the interfingering sheets appears to be thicker than the detrital facies; it may have had sufficient weight and mobility to act as a hydrostatic head, squeezing the sheets of tuff-breccia laterally into the poorly consolidated detrital beds. It is questionable, however, whether such pressure would be transmitted underground at shallow depth as much as 8 miles without the tuff-breccia breaking through to the surface and dissipating the pressure as surface mud flows. Furthermore, the part of the sheet nearest the main body of pyroclastic rock in South Fork Valley has moved relatively little, if at all, thus suggesting that injection of the peripheral portion of the sheet represents adjustment of the sheet alone.

Forceful injection might have resulted in a somewhat different way. Spreading of the pyroclastic facies over the top of the detrital sequence, near the close of Early Basic Breccia deposition, would have provided additional weight above the interfingering tuff-breccia and might have squeezed the most mobile tuff-breccia outward into the detrital facies. This mechanism does not explain injection in Greybull Valley, however, for there is no thick upper pyroclastic unit here. Furthermore, sedimentary beds overlie the slumped block northeast of Hardpan Creek; these indicate that post-depositional adjustment of the tuff-breccia occurred during deposition of overlying detrital beds rather than during eruption of the uppermost pyroclastic unit. Mud flow of the tuff-breccia may, however, have commenced with eruption from the vents and continued after deposition of the overlying beds until it became consolidated. Slumping of the block might then have occurred earlier than injection.

The evidence for forceful injection of 1–2 miles may have been wrongly interpreted, and this distance may have been much less. If so, the slight difference in density and mobility between interfingering sheets of tuff-breccia and detrital beds on a gradient increased by doming might have been adequate to cause forceful underground mud flow on a small scale.

In conclusion, the unusual structural relationships of tuff-breccia can be best explained by post-depositional movement of several sheets of tuff-breccia deposited at the surface and buried by detrital sediments. No satisfactory explanation can yet be given for the cause of this underground movement, which was probably forceful. Additional field study, both in the area here described and in the northern part of the Absaroka Range, will undoubtedly provide new data.

References Cited

Anderson, C. A., 1933, The Tuscan formation of Northern California, with a discussion concerning the origin of volcanic breccias: Univ. Calif. Pubs., Bull. Dept. Geol. Sci., v. 23, p. 215–276.

Bucher, W. H., 1933, Volcanic explosions and overthrusts: Am. Geophys. Union Trans., p. 238–242.

—— 1947, Heart Mountain problem: Univ. Wyo. Geol. Assoc., and Yellowstone-Bighorn Research Assoc., Field conference Guidebook to Bighorn Basin, p. 189–197.

Durrell, C., 1944, Andesite breccia dikes near

Blairsden, California: Geol. Soc. America Bull., v. 55, p. 255–272.
Farmin, R., 1934, "Pebble dikes" and associated mineralization at Tintic, Utah: Econ. Geology, v. 29, p. 356–370.
Hague, A., 1896, Yellowstone National Park sheets; general description: U. S. Geol. Survey G. Atlas, Yellowstone National Park Folio (no. 30).
—— 1898, Description of the Absaroka quadrangle: U. S. Geol. Survey G. Atlas, Absaroka Folio (no. 52).
Hay, R. L., 1952, The terminology of fine-grained detrital volcanic rocks: Jour. Sed. Petrology, v. 22, p. 119–120.
Pierce, W. G., 1938, Intrusive breccia along east margin of Absaroka Mountains, Wyo. (Abstract): Geol. Soc. America Bull., v. 49, p. 1896–1897.
——1941, Heart Mountain and South Fork thrusts, Park County, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 25, p. 2021–2045.
—— 1950, Source and movement of the Heart Mountain thrust blocks (Abstract): Geol. Soc. America Bull., v. 61, p. 1493.
Rock Color Chart Committee, 1948, Rock-Color chart: distributed by the National Research Council, Washington, D. C.
Rouse, J. T., 1935, The volcanic rocks of the Valley area, Park County, Wyoming: Am. Geophys. Union Trans., p. 275–284.
—— 1937, Genesis and structural relationships of the Absaroka volcanic rocks, Wyoming: Geol. Soc. America Bull., v. 48, p. 1257–1296.
Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: Jour. Geology, v. 30, p. 377–392.
Wentworth, C. K., and Williams, H., 1932, The classification and terminology of the pyroclastic rocks: Natl. Research Council Bull. 89, p. 19–53.

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STRATIGRAPHY OF THE ONONDAGA LIMESTONE (DEVONIAN) IN CENTRAL NEW YORK

By William A. Oliver, Jr.

Abstract

Detailed studies of the distribution of fossils in the Onondaga limestone (Devonian) in central New York permit division of the formation into four members each of which is subdivisible into two or more zones and several lateral facies. The Edgecliff (lowest) member is a coral biostrome over much of the State but locally passes into a bioherm facies. A basal zone of reworked sand (Springvale of various authors) is included in the Edgecliff wherever present. The Nedrow member is a shaly limestone characterized by a variety of platyceratid gastropods. The upper part of the member is a more massive limestone with a sparse fauna. The Nedrow passes westward into cherty limestone with few fossils and eastward into coarse limestone. The Moorehouse member is a massive, fine-grained limestone characterized by abundant brachiopods and certain large coiled cephalopods. This member passes west and east to coarser limestones with brachiopod-coral faunas. The base of the Seneca (upper) member is defined as the "Tioga bentonite", a prominent marker bed and an important paleontologic break. The Seneca is characterized by an abundance of *Chonetes lineatus* and few other forms. The Seneca member passes to the east into the Union Springs black shale of the overlying Marcellus formation. This relationship is indicated by the eastward thinning of the limestone and thickening of the black shale unit, and by the eastward disappearance from the top down of the Seneca zones which are recognized in the type area.

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Introduction

The Onondaga limestone extends from Ontario, Canada, south to West Virginia, and its "equivalents" west to the Mississippi Valley. Some age variation over this large area is probable. In New York it is generally considered lower Middle Devonian (Onesquethaw

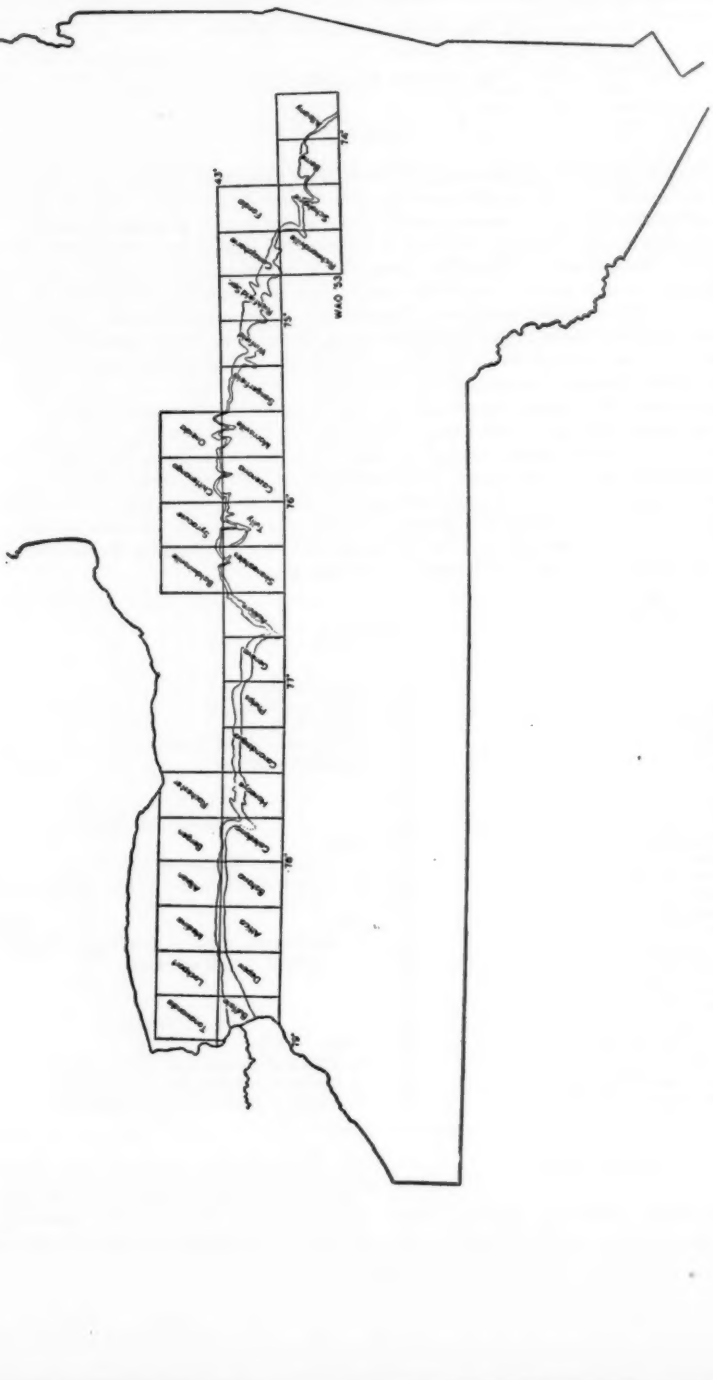

FIGURE 1.—INDEX MAP OF QUADRANGLES
Onondaga outcrop based on published maps and additional field data

stage), and is overlain by the Marcellus black shale of the Hamilton group. It is conformably underlain by the Schoharie grit, Esopus shale and Oriskany sandstone in eastern New York, but rests unconformably on the Helderberg and Upper Silurian limestones in central and western New York.

Most of the outcrops of the Onondaga have been studied from the Caledonia quadrangle to the Fonda quadrangle, but there are many gaps in information along this line because of glacial cover. Field studies were extended west to Buffalo and east to Albany (Fig. 1). The area is divided into three parts, based primarily on the geographic extent of stratigraphic units, and on the availability of information in the field. The central area as used in this paper lies between Seneca Lake (Geneva quadrangle) and Cherry Valley (Canajoharie quadrangle). Extending from this central area to Buffalo and Albany are the western and eastern areas respectively (Fig. 1).

Acknowledgments

The writer wishes to express appreciation for the guidance and assistance of Professor J. W. Wells of Cornell University, under whose direction this work was done. Dr. Winifred Goldring, State Paleontologist, New York State Museum, and Dr. R. H. Flower, formerly of the State Museum, made many helpful suggestions. I am indebted to Dr. Clarence S. Ross of the United States Geological Survey for examining several samples of the Tioga bentonite in 1951 and 1952.

Dr. Ralph Digman, temporary geologist, New York State Science Service, supplied information on thicknesses and lithology in the Berne and Albany quadrangles, including full information on the Albany and Cherry Valley well cores. Thanks are due Dr. John Broughton, New York State Geologist, for permission to use this information.

Field work in the summers of 1950 and 1951 was aided by grants from the New York State Science Service, for which grateful acknowledgment is here made. Additional financial aid was received from the Gurley Fund for Paleontology, Cornell University. Further field information was accumulated in the summer of 1952 while the writer was employed as temporary geologist by the State Science Service.

Paleontologic data are based on the writer's own collections made during the summers of 1950 and 1951, but a few specimens collected by Wells from zones known to the writer were studied. In the eastern area, data given by Goldring (1935, p. 148) were incorporated, as indicated on the faunal lists, where definite horizons were assignable.

The work was done at Cornell University as partial fulfillment of requirements for the Ph.D. degree, June 1952.

Previous Work

Inasmuch as the nomenclatorial history of the Onondaga limestone has been summarized recently by Chadwick (1944, p. 99), a detailed discussion is not deemed necessary.

Attention has been given to lithology and faunas as bases for subdivision. Eaton (1828) subdivided his "Cornitiferous Limerock" into "the lower or compact side" and "the upper or shelly side" (p. 153). These divisions, based on the occurrence of chert and abundance of fossils, roughly correspond to the "Corniferous" and "Seneca" limestones of the first New York Survey.

Vanuxem (1839, p. 274–275), working in central New York, further subdivided the Onondaga in ascending order as follows (numbered by the author):

1. "Gray sparry crinoidal limestone. 8–12′.
2. "series of shelly rotten layers of impure limestone, probably caused by an increase of the shaly matter of the gray limestone, changing all the characters, chemical, mineral and fossil which belong to that rock. 9–12′.
3. "another small series consisting of limestone . . . compact and rather brittle, generally terminated by one or two layers, containing nodules of flint, . . . arranged in parallels. 15–20′.
4. "Seneca limestone." (thickness not given.)

Conrad (1837, p. 180) in the same area recognized only two divisions: gray limestone (1, above) and blue limestone (2, 3, and 4, above).

Hall (1841, p. 156–158), working in western New York, described the following somewhat different sequence (ascending order, numbered by the present writer):

1. "Onondaga limestone", variable thickness.
2. "cornitiferous", "consists principally of hornstone 30–50′."

3. "another mass containing a little hornstone . . . resembles the compact Onondaga but . . . has different fossils."

Vanuxem (1840, p. 377) combined his divisions 2 and 3 as the "Corniferous limerock" and described the "Seneca limestone" as being characterized by "*Strophomena*" [*Chonetes*] *lineata*. Hall's name "Onondaga" was accepted for the lower "Grey Sparry" division.

In the final reports of the first survey (Vanuxem, 1842, p. 132–145; Mather, 1843, p. 337–339; Hall, 1843, p. 151–176) a two-fold division was used, "Onondaga" and "Corniferous," although Vanuxem referred to the "Seneca" as the upper part of the "Corniferous." The particular four- and three-fold divisions of Vanuxem and Hall are recognizable only in their respective districts, thus their discrepancy.

The two- or three-fold division of the Onondaga persisted for 50 years, but gradually the tendency developed to consider the whole as a single unit, since the divisions were not laterally continuous over the State.

Hall (1879, p. 140) divided "the Corniferous limestone of Eaton" in ascending order as follows (numbered by the writer):

1. "Onondaga limestone (the great coral-bearing limestone).
2. "Corniferous limestone.
3. "Cherty beds, with species of *Loxonema*, *Pleurotomaria*, *Bellerophon*, etc.
4. "Limestone with Ichthyic remains (bone bed)."

He did not discuss these subdivisions. Divisions 2, 3, and 4 represent the "Corniferous" of the first survey. Four is apparently only locally developed in the western part of the State, but the writer did not see it in the field.

Since 1900 the Onondaga has been accepted as a single unit, and little stratigraphic work has been done. Stauffer (1913, p. 85), working in Ontario, applied the name "Springvale sandstone" to the basal sandy portion of the Onondaga, which contains an Onondaga fauna and is "derived from the Oriskany by reworking of the advancing Onondaga sea." Since the same situation exists in New York, the name is applicable here, although its usefulness may be questioned. Cooper *et al.* (1942, p. 1775), in discussing the Onondaga refer to the "Seneca limestone", "This name had long fallen into disuse, but as the interval it defines is a well marked unit it is here revived." No definition of the unit is given.

Thickness

No complete exposures of the Onondaga are known from which the exact thickness can be determined; estimates of its thickness along its outcropping edge range from 50 to 200 feet. The thickness near Syracuse is approximately 70 feet. This has been determined by piecing two sections together. Individual units vary considerably over short distances, and most likely the total thickness does also.

East of Syracuse Prosser (1893, p. 96) reported 93 feet in the Morrisville well. Farther east in the Canajoharie and Albany quadrangles complete sections have recently been cored by the New York State College of Ceramics. The thickness south of Cherry Valley (Canajoharie quad.) is 118 feet and near Albany is over 111 feet (Ralph Digman, personal communication). These figures indicate a general eastward thickening from the type area.

A similar thickening west of the type area is indicated by the increase in size of the individual members. Luther (1894, p. 240–241) reported 140 feet in the Livonia Salt Shaft (Honeoye quad.) and similar thicknesses in other shafts 15 miles farther west. There is little reason to question his results, for he studied the fossils and lithology as the shaft was dug.

Farther west the thickness is uncertain as complete sections of three of the four members are not known. Many well thicknesses have been published, but these are mostly based on drillers' reports. The base of the formation is hard to determine in a well when the Oriskany sandstone is absent. Bishop (1897, p. 389) said that the "Flint" of the drillers included the upper Silurian waterlimes as well as the Onondaga. He concluded that the average thickness in Erie County (Buffalo) is 108 feet.

Field evidence indicates that the formation does not continue to thicken west of the salt shafts. The calculated thickness at Leroy (Caledonia quad.) is 145 feet, based on a southerly dip of 30 feet per mile. This compares with well thicknesses of 137 and 146 feet

reported by Bishop (1886) from Leroy and 4 miles south of Leroy. Farther west the thickness is not known, but it probably does not exceed 150 feet and may be considerably less if Bishop's interpretation is correct.

Type Section

The type section of the Onondaga was not designated by Hall who named the unit, or by any of the other early workers who accepted Hall's term and by their usage helped define it. The term as first used was more restricted than it is now. Evidently, Hall took the name from Onondaga County, New York (Wilmarth, 1938, p. 1550). Chadwick (1944 p. 99) stated that the type locality was Split Rock, just west of Syracuse, but the reason for this designation is not given, and, since only the lowest member of the Onondaga is fully exposed there, it is not adequate. The type locality should remain simply "Onondaga County," where nearly the whole formation is exposed at various places south of Syracuse.

Basal Contact

Westward across New York the Onondaga rests on successively older formations. In the Albany-Schoharie area the contact is gradational, and there is a facies relationship between the Onondaga and Schoharie formations (Clarke, 1902, p. 667; Ruedemann, 1930, p. 177; Goldring, 1931, p. 383; 1935, p. 212). The westernmost known exposure of the Schoharie is in the northwest corner of the Richmondville quadrangle, where phosphate nodules indicate slight disconformity. In the east, and for some distance west of Cobleskill, the Schoharie and Onondaga formations overlie the Oriskany, Esopus, and Carlisle Center formations, apparently with only slight disconformity, if any. West of the Richfield Springs quadrangle, where the Esopus and Carlisle Center wedge out, the Onondaga overlies successively the Oriskany sandstone, Helderberg limestones, and the Manlius (upper Silurian) limestone. This unconformity has been extensively discussed (Grabau, 1900; Harris, 1904; Kindle, 1913; Smith, 1929).

At almost all the localities west of Richfield Springs where the lowest Onondaga is exposed, a sandy zone (Pl. 1, zone A) at the base of the formation ranges in thickness from an inch to several feet and grades upward into the limestone. Early workers in central and western New York referred this sandstone to the Oriskany formation (*e.g.*, Luther 1906, p. 11; 1911, p. 8), but it contains the typical Oriskany fauna in only a few spots. Immediately above the underlying formation, where the sand concentration is greatest, few fossils are seen. As the bed becomes more limy, however, fossils become common. The fauna of this basal zone consists of typical Onondaga forms. In recent years this sand has been recognized as basal Onondagan, formed by reworking of the Oriskany deposits in the early Onondaga sea. Phosphate nodules and fragments of the lower limestones are not uncommon in this reworked zone. A multiple unconformity involving a considerable span of time is involved, but pre-Onondaga erosion involved only the partial removal and reworking of the Oriskany sandstone; pre-Oriskany erosion had removed the Helderberg and upper Silurian limestones. Stauffer (1913, p. 85) proposed the name Springvale sandstone member for the basal sandy beds of the Onondaga limestone in Ontario, and Chadwick (1919, p. 42) extended its usage to New York.

Remnants of Oriskany and Schoharie faunas have been reported locally from the basal Onondaga. Schuchert (1889, p. 397–400; 1900, p. 323–326) described a fauna of mixed Oriskany and Onondaga types from Cayuga, Ontario. Ulrich and Schuchert (1902, p. 653) designated these beds the Decewville formation, and they and others (*e.g.*, Weller, 1909, p. 261) based their paleogeographic-faunal migration theories on this occurrence. Stauffer (1912, p. 371–376), however, showed that the Onondaga forms were restricted to the reworked sandy zone while Oriskany forms were limited to the underlying, true Oriskany sandstone.

The lowest faunal unit of the Onondaga over most of New York is a zone dominated by corals (zone C). This is replaced in places by a brachiopod fauna. Such a fauna is developed at Jamesville (southeast of Syracuse) in the reworked sand zone (A). Corals and brachiopods

are equally common. The identified species are listed in Table 1.

Clarke (1894, p. 349) and Luther (1894, p. 241) list a remarkably similar fauna (few corals and including *Costispirifer arenosus*) from the sandstone in the Livonia Salt Shaft (Honeoye quad.) and suggest a mixture of Oriskany and Schoharie elements. A third, somewhat similar, occurrence is at Clarence Hollow (Depew quad.). The brachiopod element is not so well developed, but Hall (1867, p. 203) described a specimen of "*Spirifer unica*" from this locality. According to Ulrich and Schuchert (1902, p. 653), this is probably *C. arenosus*, a typical Oriskany form, also occurring at the above two localities.

These three occurrences are reminiscent of the Oriskany in the rough water, sandy environment indicated, and by the presence of *Costispirifer arenosus*. *C. arenosus* might have been deposited with the Oriskany sandstone and later reworked and mixed with Onondaga forms, or the specimens might represent individuals which lived on into early Onondaga times in the sandy environment to which they were adapted. The former seems unlikely as the writer's specimen is in a condition of preservation similar to the associated Onondaga forms. The latter is supported by the fact that the other associated branchiopods are somewhat larger than those found in the higher limestone, an adaptation to the rough water, sandy environment. If environment similar to that of Oriskany time did characterize the initial Onondaga deposits then *C. arenosus* itself might be represented, or modification sufficient to form a new species (*C. unica*) might have taken place as implied by Hall.

Farther west two other, somewhat different, occurrences are notable. In the northeast corner of the Depew quadrangle and in the northern part of the Caledonia quadrangle a brachiopod fauna is developed in the lower limestone proper (Pl. 1, zone B). The sandy zone is thin or missing, but the lower 2 feet of the formation contains numerous brachiopods and relatively few corals. *Costispirifer arenosus* is present, but the Onondaga forms differ greatly from the three occurrences described in the preceding paragraph. The forms that have been identified are listed in Table 1.

Stauffer (1915, p. 15–20) listed a similar fauna from the lower 20 feet of the Onondaga, just west of the Niagara River in Ontario. There, the brachiopod beds thin and disappear a few miles farther west. Stauffer suggested that these beds represent a lower member of the Onondaga not everywhere deposited. If Stauffer is correct, the Caledonia quadrangle outcrop would represent the easternmost exposure of this member. The member must be discontinuous, however, for no such basal fauna has been found in the intervening areas where the coral fauna forms the basal zone. Stauffer's brachiopod beds are the "lower fauna" in western New York of Cooper *et al.* (1942, p. 1774) and Flower (1943, p. 1830). These authors suggest a Schoharie relationship.

The presence of these dominantly brachiopod thanatocoenoses below the usual basal coral zone suggests a local survival and westward extension of Schoharie elements in earliest Onondaga times. Their stratigraphic position suggests such a correlation. The Schoharie fauna (Grabau, 1906, p. 180–192) is remarkably similar to the Onondaga fauna in its brachiopod elements, and almost all the brachiopods listed from the Depew occurrence (Table 1, zone B) are found in the Onondaga elsewhere, as well as in the Schoharie grit of eastern New York. The Schoharie grit, however, is particularly noted for its cephalopods. The absence of cephalopods from the western occurrences, as well as the presence of Onondaga corals, leaves the above interpretation open to question.

Central New York Section

Edgecliff Member

The lowest member of the Onondaga in the central area is a massive, light-gray (in some places pink), very coarsely crystalline limestone, characterized in this area by a profusion of tabulates, large rugose corals, and crinoid columnals. This unit is a true coral biostrome, largely made up of coral skeletons in a matrix of crinoidal debris. This is Hall's (1879, p. 140) "great coral bearing limestone" and the "Onondaga limestone" of early reports.

This unit is here designated the Edgecliff member from exposures at Edgecliff Park,

southwest of Syracuse and 1 mile northeast of Howlet Hill, Camillus (7½ minute) quadrangle. Between Edgecliff Park and Split Rock, 2 miles farther east, is an almost continuous exposure of this member. It is most accessible at Split Rock, but this name is preoccupied.

The biostrome ranges in thickness from 8 feet at Split Rock to 25 feet at Chittenango Falls (Cazenovia quad.). The variations in thickness are irregular, but a general eastward thickening is noticeable (Pl. 1). The base of this unit is very sandy in most places (zone A, Springvale horizon). The sandy zone ranges from a fraction of an inch thick with only widely scattered grains to 4 feet with a high enough sand concentration at its lower limit to make it a sandstone. Everywhere this sandy zone carries an Onondaga fauna and is easily distinguished from the true Oriskany sandstone. Very light-colored, whitish-gray chert nodules are found widely and irregularly spaced in the limestone (zone C). This chert is more characteristic of the upper half of the Edgecliff but may occur in the lower part also.

The Edgecliff fauna (Table 1) is dominated by comparatively few species of tabulate and rugose corals. Very large crinoid columnals, up to 1 inch in diameter, are characteristic. Small columnals form the matrix and predominate in the upper half of the biostrome. Brachiopods are not common, but most collections show a few specimens. Bryozoa are present in most sections but are not prominent. Gastropods and trilobites are rare. A few stromatoporoids were found.

The broad-based colonial tabulates are found in an upright position, but most of the solitary rugose corals are overturned and show some signs of post-mortem wear. The Edgecliff environment was particularly well adapted for the growth of corals. The relatively pure, thick-bedded biostromal limestone with a few greenish shaly partings indicates clear water and fairly constant conditions, interrupted at rare intervals by minor influxes of mud, causing temporary cessation of coral growth. Resumption of normal conditions permitted a new "bloom" of corals, ultimately forming another thick bed. Crinoids apparently grew among the corals and in later Edgecliff time seem to have dominated the scene. Present variations in thickness indicate that the biostrome had a broadly undulatory surface, but there is no evidence that any knobs or knolls were raised prominently above the general plane of deposition as true reef structures. The sea bottom was covered by "forests" of corals which were so well adjusted to existing conditions that they excluded most other forms of life.

Nedrow Member

Overlying the Edgecliff member throughout the central area is 10–14 feet of thin-bedded and shaly limestones marked in the lower part by abundant platyceratid gastropods. These are Vanuxem's (1839, p. 275) "series of shelly rotten layers of impure limestone, ..." Hall (1879, p. 29) referred to the profusion of gastropods in these beds at "Onondaga" (south of Syracuse), and Schneider (1894, p. 31) mentioned them. These beds are designated the Nedrow member, from the typical locality 1 mile south of Nedrow, at the Indian Reservation Quarry, between Quarry Road and U. S. 11, just south of their intersection (South Onondaga, 7½ minute quad.; Tully, 15 minute quad.).

The contact between these beds and the underlying Edgecliff member is very sharp (Fig. 2). The Nedrow beds are medium gray, very fine-grained, and argillaceous. Fossils are abundant; gastropods are most prominent because of their variety, but brachiopods actually exceed them in numbers. The member can be roughly divided into a lower very shaly part (zone D) that bears the gastropods and ranges from 2 to 5 feet thick, and an upper part (zone E) that is characterized by many of the same brachiopods and the absence of the gastropods and is thicker-bedded and less argillaceous (Pl. 1). Zone E grades into the next higher member; the contact is marked by the disappearance of certain species rather than by a lithologic break. Chert is not common in this member, but scattered, medium- to dark-gray nodules are found in zone E at certain localities.

Zone D, the *Platyceras* zone, is characterized by a great variety of platyceratid gastropods with but few specimens of a given species. Most of the species have not been found elsewhere

in the Onondaga. The beds are also characterized by a low turbinate form of *Heliophyllum halli* and by *Amplexiphyllum hamiltoniae*, both rugose corals rare elsewhere in the Onondaga. Brachiopods are very common as a group, but many species are represented by few individuals. One trilobite is common. The comparatively few individuals of a great variety of gastropods and brachiopods indicate optimum conditions for mud-tolerant forms.

Zone E marks a time of increasingly difficult conditions for these animals. Gastropods and corals are rare. Brachiopods are common; fewer species are represented, but there are more individuals. Such a reversal of faunal statistics from numerous species with few individuals to few species with numerous individuals is characteristic of less favorable living conditions with sharp competition for survival.

Moorehouse Member

Overlying the Nedrow member and transitional from it is 20–25 feet of medium-gray, very fine-grained limestone beds in many places separated by thin shaly partings. The individual units range from 2 inches to 5 feet thick. The unit is designated the Moorehouse member from the type locality on the southwest extremity of Moorehouse Flats at the Onondaga County Prison Quarry, half a mile south of the County Penitentiary at Jamesville (Jamesville, 7½ minute quad.; Tully, 15 minute quad.).

Chert is common in this member, but varies in amount. It is dark gray and forms more or less continuous strata 1–5 inches thick. At some exposures chert is common, while near by at the same horizon only a few beds occur (Pl. 1). It is generally present in the lower half of the member, but is more abundant in the upper half. On this and on a faunal basis the member can be divided into two zones (F and G) of approximately equal thickness.

Zone F is characterized by a relative paucity of fossils. Most of the species from this zone are more common in other members. No species is limited to this zone, and none is particularly characteristic of it. Almost all of the few species identified are of frequent or common occurrence; few are rare. Again there is an indication of less favorable times, the fauna consisting of those few forms which could most successfully live under such conditions.

Zone F is transitional to zone G, but the latter bears a distinctive faunal assemblage, with the largest number of species identified from any zone, exceeding even the *Platyceras* zone (D) in variety. Many species first appear here (Table 1). *Bellerophon* sp., "*Pleurotomaria*" sp., *Loxonema sicula*, and *Coleolus crenatocinctum* are especially characteristic. These four commonly occur in the chert and in the limestone proper. The latter two are common in the next higher member as well. *Halloceras undulatum*, a large coiled nautiloid, is also characteristic. A return to optimum conditions is indicated by the fauna. Conditions differed markedly from those of zone D, as is indicated by the lithology. Zone G is not shaly and contains considerable chert. The importance of the latter is indicated by the association of the above four gastropods with it. A similar association in the Eversole Chert member of the Columbus limestone of Ohio has been noted by Stauffer (1909, p. 35–36, 72–74).

On certain bedding surfaces in zone G, and locally in zone F, are indications of wave action and concentration of coarse fossil debris. The lines of fossil concentration make a pattern on the surface of the bed similar to mud cracks. Apparently these beds were deposited near wave base so that minor shifts of conditions would cause deposition to be followed by a wave stirring of the fresh sediments, the coarser fossil fragments settling out first and concentrating along certain pre-existing lines (submarine mud cracks?). The debris consists mainly of crinoid columnals and fragments of larger fossils. Similar "mud crack" fillings have been reported from the Columbus limestone of Ohio, where fish bones are a prominent constituent of the concentrate (Wells, 1944).

The Moorehouse member marks a return to favorable benthonic ecologic conditions and is the reverse of the Nedrow member. Zone D is ecologically comparable to zone G, with the depleted zones E and F intervening. D and G are both characterized by gastropods, although numerically dominated by brachiopods. They differ, however, in the types of gastropods and brachiopods and in the lithology. Optimum though differing ecologic conditions, perhaps

deeper water, plus time, caused the appearance of an analogous, but only distantly related, fauna. Zone E represents the concluding phase of the Nedrow fauna, while zone F introduces the new Moorehouse fauna. Each is dominated by brachiopods which appear in the related gastropod zones in larger numbers, associated with several other forms.

Seneca Member

Extending from west of the central area to Cherry Valley (Canajoharie quad.) and resting on the Moorehouse member is a series of beds lithologically similar to those of zone G, but characterized by *Chonetes lineatus*, associated with comparatively few other forms. Only one species, *Chonostrophia reversa*, is limited to this member in this area, but *C. lineatus* and one or two other species are essentially limited to it; only rare specimens are found in the top of zone E.

The earliest workers noted the abundance of *Chonetes lineatus* in the upper Onondaga of central New York. This form was the basis for naming the Seneca limestone although the interpretation of that unit has varied. Vanuxem (1839, p. 275–278) named the member from exposures in Seneca County (Geneva quad.). Vanuxem (1840, p. 377; 1842, p. 144) and Hall (1839, p. 293) defined the Seneca as containing *"Strophomena" lineata* and few other forms, evidently corresponding closely to the member as here defined. Copper *et al.* (1942, p. 1774–1775) revived the term and described it as follows:

> "In central New York a third division of the Onondaga, the Seneca Limestone, is a dark shaly rock underlying the Marcellus and containing an abundance of *Chonetes lineatus*, *Dalmanites selenurus* and large coiled cephalopods."

C. lineatus is essentially limited to zones I and J (lower Seneca), while *Odontocephalus selenurus* is common from zones E through I (Nedrow-Moorehouse-Seneca), and the large coiled cephalopod, *Halloceras undulatum*, characterizes zone G (Moorehouse). Thus Cooper included much more in the "Seneca" than did the early workers who defined it.

At the base of this member is a remarkably uniform bed of clay 6 inches thick (Pl. 1, zone H). This clay is an ochre color when fresh or nearly so, but at most localities is badly weathered to a dull gray. The bed is marked by a recess at each exposure, the clay usually having been weathered back 1–2 feet from the face of the tiers above and below. It is unfossiliferous.

This clay bed was first noted by Hall (1843, p. 163) in the Waterloo area (Geneva quad.). He described it as laminated and yellowish. Delafield (1850, p. 448) mentioned a "talcose shaly clay" in the same area. Luther (1894, p. 240) mentioned a "soft layer" at about the same horizon in the Livonia Salt Shaft (Honeoye quad.) and mentioned its occurrence at the Greigsville and Lehigh shafts also. He suggested that it might be of volcanic origin. Lincoln (1895, p. 91) gave the fullest discussion of the bed and mentioned its occurrence at Union Springs (Auburn quad.) as well as at Waterloo. He described it as follows:

> "eight inch layer of light greenish grey material, called 'marl' by the workman, which is constant; . . . It has somewhat the look, but not the feel of soapstone; breaks in small, flat, thick bits and cuts easily. It is not plastic. It is a nonhydrated aluminum silicate; a clay containing small quantities of lime and magnesia."

Luther (1909, p. 14) again mentioned the bed in the Waterloo area but did not suggest its correlation with the bed in the salt shafts.

This clay bed is the Tioga bentonite which has been recognized in the subsurface throughout Pennsylvania and adjacent areas of West Virginia, Ohio, and southwest New York. The extent of this bed has been recently discussed by Flowers (1952) and Fettke (1952). Fettke reports the bentonite at the top of the Onondaga in central Pennsylvania and 30 feet below the top in the western part of the state. Subsurface samples of this material have been examined and confirmed by C. S. Ross (Flowers, 1952, p. 2037–2038).

Surface exposures of the bentonite in New York are deeply weathered, and clean samples are rare. Some of the best material was submitted to Doctor Ross for examination late in 1951. He reported (personal communication, April 1952) no definitely recognizable shard structures but a "very strong possibility that it is derived from volcanic ash." In the summer

of 1952 the bentonite was found in a core made by the New York State College of Ceramics near Cherry Valley. This material was submitted to Doctor Ross late in 1952. He said (personal communication, February 1953) that the material gave "clear cut evidence of volcanic origin" and he compared it to the West Virginia material of Flowers.

The probable origin of this bed and its persistence over so great an area makes it an important reference plane. Such a thin unit, differing so markedly from the limestone above and below and from the often fossiliferous shaly partings, is essentially a time plane to which other horizons can be referred.

In addition to the marked lithologic break of the bentonite, a sharp faunal break is the basis for separating the Moorehouse from the Seneca member. About 25 species of zone E (some originating in that zone and others coming up from lower zones) are not found above the bentonite in the central area. Lithologically, these beds are similar to the lower zone although a somewhat darker gray in many localities. The higher beds are thinner and in places approach a shaly limestone. Dark-gray chert is common in the lower part and extends through the whole member as scattered nodules. A limited chert-gastropod association is again noted. Faunally and lithologically the member can be divided into five zones, the lowest being the Tioga bentonite (zone H) already discussed.

Zone I is lithologically similar to zone G. Faunally it differs in the small number of species represented and in the first common occurrence of *Chonetes lineatus*. This zone is 8 feet thick.

Zone J is the "Pink *Chonetes* zone" of various authors. Lithologically it is a very thin-bedded limestone, about 4 feet thick and composed almost entirely of the shells of *C. lineatus*, many of which are stained pink. Associated with *C. lineatus* are a few other scarce forms. About 6 inches below the top of this zone at most localities is a bed of chert, similar to that of zone I. Here it usually includes *Coleolus crenatocinctum* and *Loxonema sicula*. Most of the other brachiopods in the faunal list and a very few specimens of *C. lineatus* also are found in the chert. The concentration of *C. lineatus* continues above the chert for 6 inches, but few specimens are found higher in the section. In this uppermost part of zone J is the first common occurrence of *Chonostrophia reversa*.

Overlying zone J is a series of limestone beds which tend to be dark gray (zone K). The color darkens upward throughout the Seneca member, and no sharp difference is noted between successive zones. Chert is less common. Fossils are increasingly scarce from the base to the top of this zone. Immediately over the Pink *Chonetes* zone (J) is a concentration of small zaphrentid corals (Fig. 2) referred to here as *Heterophrentis* sp. B. This species is common from zone D to this horizon, but is especially notable for its persistence at the base of zone K. *Chonostrophia reversa* is very common in the lower part of zone K and continues to the top of it. Other forms are uncommon or rare. The Seneca member is exposed at many localities in this area, but the top of most sections is in the middle of this zone (K), the Marcellus shale and upper shaly beds of zone K having been removed. The full Seneca member is exposed only near Union Springs (Auburn quad.) and at Stockbridge Falls (Morrisville quad.). At Union Springs the thickness of zone K is 9 feet; *Chonostrophia reversa* is common throughout. At Stockbridge Falls, 55 miles east, zone K is represented only by a few inches of shaly limestone between zone J and the Union Springs member.

The Onondaga-Marcellus contact is gradational near Union Springs (Fig. 2). The top of zone K is labelled *a* on the section. The top of the Onondaga according to Clarke (1901, p. 119), Cleland (1903, p. 20), and Cooper (1930, p. 132) is indicated by *e*. Above *a* the sequence is: *b*—very dark shale, no fossils found; *c* and *d*—two very dark limestone tiers, no fossils found. The contact was set at *e* by the above individuals probably because this is the base of the first real black shale (*f*). Above *e* an alternation of very dark limestone and black shale is as indicated in the figure. Beds *g* and *h* are the highest limestone layers which could be referred to the Onondaga. Above bed *h* the section is essentially all black shale. At Union Springs no fossils were found in these beds, probably because of difficulty in collecting

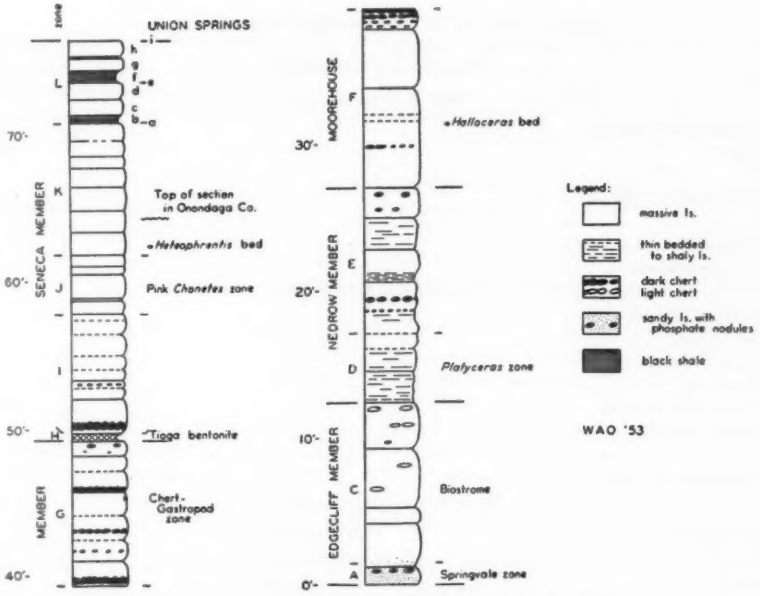

FIGURE 2.—COMPOSITE LITHOLOGIC SECTION IN THE TYPE AREA

Edgecliff, Nedrow, and Moorehouse based on outcrops in the Tully quadrangle. Seneca based on exposures near Union Springs (Auburn quadrangle).

from the sheer quarry wall. Twenty miles east, however, near Marcellus (Skaneateles quad.), the following sequence is exposed:

	Feet	Inches		
6. Cherry Valley limestone	3			
5. Union Springs black shale	10			
4. limestone bed		3	*Chonetes lineatus*	c
3. limestone bed		6	*Chonostrophia reversa*	r
			Levenia lenticularis	r
2. black shale		1		
1. limestone bed covered lower		12		

Beds 1–4 appear to correlate with beds *g* and *h* of the Union Springs section. The fauna of these beds is Onondagan, and the Marcellus contact should be placed above those beds (*i* on the section). The 6 feet of very dark, bituminous limestones and included black shales above zone K are here referred to zone L of the Seneca member.

Ecologically, the Seneca member marks a decline of the generally favorable conditions in the Onondaga sea. The early stages of black-mud deposition are indicated by the increasingly dark and shaly sequence from the bottom to top of this member. The lowest zone (I) is most fossiliferous. Each succeeding zone contains fewer species. Zone I contains a large proportion of species that are abundant. Species and individuals become less common higher in the section. The overwhelming abundance of *C. lineatus* throughout the zone is indicative of the unusually difficult conditions for which this form was adapted.

Faunal Succession

Table 1 lists the complete central area fauna identified by the author from each of the members and zones. Each list is in the same taxonomic order to be easily comparable with the adjacent ones.

TABLE 1.—FAUNA OF CENTRAL NEW YORK SECTION*

EDGECLIFF MEMBER

ZONE A (SPRINGVALE)

Heterophrentis prolifica	c
H. sp. A	r
Fistulipora cf. *sphericus*	r
Pentamerella arata	c
Atrypa reticularis	x
Costispirifer arenosus (=*unica*) (characteristic of the Oriskany formation)	r
"Spirifer" duodenarius	r
"Sp." macer	r
Elytha fimbriata	x
Athyris sp.	r
Schuchertella pandora	r
Chonetes deflectus	r
Platyostoma sp. indet.	r

ZONE B (*Amphigenia* ZONE)

Favosites basalticus	r	*Meristella* cf. *scitula*	c
F. emmonsi	r	*Stropheodonta inequiradiata*	r
F. limitaris	r	*Leptostrophia perplana*	c
F. turbinatus	r	*Leptaena rhomboidalis*	r
		Schuchertella pandora	x
Heterophrentis complanata	r	*Chonetes* sp.	r
H. prolifica	c	*Levenia lenticularis*	x
Homalophyllum exigum	r	*Amphigenia elongata*	vc
Breviphrentis yandelli	r	*Centronella glansfagea*	vc
Scenophyllum conigerum	r		
Bethanyphyllum robustum	r	*Platyostoma lineata*	r
Cystiphylloides americanum	r	*Platyceras carinatum*	r
C. sulcatum	r	*Orthonychia concavum*	r
		O. dentalium	r
Atrypa reticularis	r		
Costispirifer arenosus	r	*Phacops cristata*	r
"Spirifer" duodenarius	vc	*Odontocephalus selenurus*	x
Elytha fimbriata	r		

ZONE C (BIOSTROME)

Favosites limitaris (locally)	c	*C. sulcatum*	r
F. basalticus	c	*C.* cf. *conifollis*	c
F. turbinatus	x		
F. emmonsi	x	Stromatoporoid	vr
F. epidermatus	r		
F. canadensis	r	Bryozoa spp.	x
F. sp.	r		
Coenites sp.	x	*Lingula* sp.	vr
Aulopora sp.	r	*Pentamerella arata*	r
Syringopora sp.	x	*Atrypa reticularis*	r
		Coelospira camilla	vr
Heterophrentis prolifica	vc	*"Spirifer" raricosta*	x
H. sp. A	vr	*"Sp." duodenarius*	vr
H. sp.	r	*Meristella nasuta*	r
Siphonophrentis gigantea	r	*M. doris*	?

TABLE 1.—(*Continued*)

Breviphrentis yandelli	x	*Leptaena rhomboidalis*	r
Bethanyphyllum robustum	vc	*Schuchertella pandora*	r
Blothrophyllum decorticatum	r	*Chonetes* cf. *hemisphericus*	vr
B. promissum (common to east)	r	*Levenia lenticularis*	?
Heliophyllum halli	r	*Amphigenia elongata*	vr
H. sp. B	r		
H. sp.	vr	*Pleurotomaria arata* var. *clausa*	vr
Synaptophyllum simcoense	x	*Platyceras* sp.	vr
Cystiphylloides americanum	vc		
		Phacops cristata	vr

NEDROW MEMBER

ZONE D

Favosites basalticus	vr	*M.* sp. (locally)	c
Aulopora sp.	vr	*Pentagonia unisulcata*	vr
Romingeria sp.	r	*Megastrophia concava*	vr
		Stropheodonta inequiradiata	vr
Amplexiphyllum hamiltoniae	c	*Leptaena rhomboidalis*	r
Heterophrentis prolifica (locally)	c	*Schuchertella pandora*	vr
H. sp. B	c	*Chonetes mucronatus*	vr
H. sp.	r	*Levenia lenticularis*	vr
Bethanyphyllum sp.	vr		
Heliophyllum halli	c	*Platyostoma lineata*	c
Cystiphylloides americanum	vr	*P. turbinata*	c
C. sp.	r	*P. unisulcata*	r
		Platyceras fornicatum	x
Stromatoporoid	vr	*P. rictum*	x
		P. dumosum var. *rarispinum*	x
Bryozoa	x	*P. argo*	r
Fenestella sp.	r	*P. erectum*	r
		P. sp.	x
Pentamerella arata	vr	*Orthonychia conicum*	x
Camarotoechia tethys	vr		
Atrypa reticularis	c	*Phacops cristata*	c
Coelospira camilla	vr	*Odontocephalus selenurus*	x
"Spirifer" raricosta	x		
Meristella nasuta	r	Ostracod spp.	x

ZONE E

Favosites turbinatus	vr	*Stropheodonta inequiradiata*	vr
Ceratopora sp.	vr	*Leptostrophia perplana*	x
		Schuchertella pandora	vr
Amplexiphyllum hamiltoniae	r	*Chonetes mucronatus*	x
Heterophrentis prolifica	vr	*Productella navicella*	vr
H. sp. A	vr	*Strophalosia* ? sp. (locally)	c
H. sp. B	r	*Levenia lenticularis*	c
Bryozoa	r	*Platyostoma lineata*	r
		P. turbinata	vr
Lingula desiderata	vr	*Platyceras dumosum* var. *rarispinum*	vr
Atrypa reticularis	c		
Coelospira camilla	x	*Halloceras undulatum*	vr
Anoplotheca acutiplicata	x	*Odontocephalus selenurus*	c
		Ostracods	x

TABLE 1.—(*Continued*)

MOOREHOUSE MEMBER

ZONE F

Amplexiphyllum hamiltoniae	vr	*Chonetes mucronatus*	x
Heterophrentis sp. A	c	*Levenia lenticularis*	c
H. sp. B	x		
H. sp.	x	*Platyostoma lineata*	x
		Platyceras sp.	r
Bryozoa	x		
		Halloceras undulatum (locally)	c
Atrypa reticularis	x		
"Spirifer" duodenarius	?	*Phacops cristata*	x
Leptaena rhomboidalis	x	*Odontocephalus selenurus*	c
Schuchertella pandora	c		
		Ostracods	x

ZONE G

Favosites sp.	r	*Leptostrophia perplana*	vc
Pleurodictyum convexa (locally)	c	*Leptaena rhomboidalis*	x
Aulopora sp.	r	*Schuchertella pandora*	c
Ceratopora sp.	r	*Chonetes lineatus*	r
Syringopora sp.	r	*C. mucronatus*	vc
		Productella navicella	x
Heterophrentis prolifica	r	*Levenia lenticularis*	vc
H. sp. A	c	*Isorthis propinqua*	x
H. sp. B	c		
		Cypricardella ? sp. A	vr
Bryozoa	x		
Fenestella sp.	vr	*Bellerophon* sp.	c
		"Pleurotomaria" sp.	c
Lingula desiderata	r	*Euomphalus* cf. *clymenioides*	vr
"Discina" minuta	vr	*Loxonema sicula*	c
Pentamerella arata (to east only)	x	*Platyostoma lineata*	vr
Atrypa reticularis	c		
A. spinosa	r	*Coleolus crenatocinctum*	vc
Coelospira camilla	vr	*Tentaculites scaleriformis*	vr
Anoplotheca acutiplicata	c	*Styliolina fissurella* (locally)	c
Elytha fimbriata (to east only)	x		
"Spirifer" duodenarius	?	*"Orthoceras"* sp.	r
"Sp." raricosta (to east only)	x	*Halloceras undulatum*	c
Meristella doris	r	*Ovoceras* sp.	vr
M. nasuta	?	breviconic ceph.	vr
M. sp. A	c		
Pentagonia unisulcata	r	*Phacops cristata*	c
Athyris spiriferoides	c	*Odontocephalus selenurus*	c
Megastrophia concava	r		
M. hemisphaerica	vr	Ostracods	c
Stropheodonta inequiradiata (to east only)	x		

SENECA MEMBER

ZONE H (TIOGA BENTONITE)

No fossils seen

ZONE I

Amplexiphyllum hamiltoniae	x	*Schuchertella pandora*	x
Heterophrentis sp. B	c	*Chonetes mucronatus*	vc
		C. lineatus	vc

TABLE 1.—(*Continued*)

Bryozoa	x	*Levenia lenticularis*	c
Coelospira camilla	x	*Coleolus crenatocinctum*	c
Anoplotheca acutiplicata	vr		
Meristella ? sp. A	c	*Odontocephalus selenurus*	c
Athyris spiriferoides	vr		
Leptaena rhomboidalis	vr	Ostracods	x
ZONE J (PINK *Chonetes* ZONE)			
Amplexiphyllum hamiltoniae	vr	*Chonostrophia reversa*	c
Heterophrentis sp. B	c	*Chonetes lineatus*	vvc
		Levenia lenticularis	r
Atrypa spinosa	vr		
A. reticularis	vr	*Loxonema sicula*	x
Coelospira camilla	vr		
Meristella ? sp. A	x	*Coleolus crenatocinctum*	x
Schuchertella pandora	vr		
ZONE K			
Amplexiphyllum hamiltoniae	x	*Schuchertella pandora*	vr
Heterophrentis sp. B	c	*Chonostrophia reversa*	vc
		Chonetes lineatus	x
Coelospira camilla	vr	*C. mucronatus*	vr
Meristella ? sp. A	vr	*Levenia lenticularis*	x
ZONE L (SKANEATELES QUADRANGLE)			
Chonetes lineatus	c		
Chonostrophia reversa	x		
Levenia lenticularis	x		

* The following symbols are used:
vvc abundant (crowded in rock)
vc very common (common throughout zone)
c common (present or common at most exposures of zone)
x frequent (few specimens found at most exposures of zone)
r rare (uncommon, found at approximately half the exposures)
vr very rare (one or two specimens at few localities)

WESTERN NEW YORK SECTION

Edgecliff Member

The Edgecliff is recognizable as far west as Buffalo. The main changes are in thickness and amount of chert. Zone A, the Springvale sand zone, is present at most localities where the lower contact is exposed but is very thin, and in some of the more western exposures is missing (Pl. 1). The greatest thickness is in the Livonia Salt Shaft (Luther, 1894, p. 241) where it has a brachiopod fauna. (*See* section on basal contact.) Zone B, with its *Amphigenia* fauna, is lenticular and has been seen at only two localities.

Zone C, the coral biostrome, is continuous across the western area. Its thickness varies, and it contains more light-gray chert than in the central area. Immediately west of Seneca Lake (Geneva quad.) the light-gray, coarse, crystalline limestone interfingers with the dark, cherty Nedrow member (Pl. 1). In the Phelps, Canandaigua, and Honeoye quadrangles, several sections show this alternation, while intermediate sections show a sharp contact. Evidently Nedrow deposition began early in some areas, while Edgecliff conditions persisted in others. Intermediate areas were alternately subjected to Edgecliff and Nedrow conditions. The zone C fauna (Table 2) is essentially the same as that of the central area.

In the extreme western part of the State near Buffalo, the Edgecliff has a different facies. Near Williamsville (Buffalo quad.) there is at least one large biohermal ("reef") structure, described by Grabau (1903, p. 340–341; 1932,

p. 424). It is a lens-shaped body, 35 feet thick (Luther, 1906, p. 12–13) and several hundred feet in diameter. The limestone looks like that of the biostrome, but the bedding is extremely irregular except near the edges where biostromal beds dip away at angles of 10° or more (Grabau, 1932, p. 425). The fauna differs from that of the biostrome (Table 2). Solitary rugose and tabulate corals and crinoids dominate the latter, while colonial rugose corals, stromatoporoids, and gastropods are additional important elements in the bioherm facies. In the fringing areas the solitary forms regain their dominance, and more brachiopods are seen.

Small "micro-reefs" are exposed in the biostrome at Clarence (Depew quad.) 12 miles east of Williamsville. The surface of one bed, exposed over a broad area, shows numerous mounds, each about 18 inches high and 6–8 feet in diameter. The mounds are more crowded with corals than the intervening areas and seem to represent very local centers of prolific coral growth.

The ecologic conditions of the central area in Edgecliff times extended west to the Buffalo area. The bioherm, however, represents even better conditions for coral growth. Not only was the situation so favorable for all types of corals and crinoids that they were able to exclude other types, but growth was so fast that a reeflike structure was built above the general level of sedimentation. These conditions were unmatched in the Onondaga seas except in the Helderberg area where similar structures are exposed. Grabau (1932, p. 424) and many other authors have referred to the lower Onondaga coral beds as representing coral reefs. He envisioned a series of barrier reefs roughly parallel to the southeastern shore line with westward-moving lagoonal conditions following the coral growth. Over much of the State the biostrome structure is a bedded deposit of slight relief. The Williamsville bioherm is hardly large enough to suggest a barrier reef. Additional accurate subsurface data are necessary to determine the paleogeographical relations of the bioherms, but the surface evidence indicates that they represent only more or less isolated areas of unusually abundant and specialized coral growth.

The *Platyceras* fauna of the overlying zone D (central area) is not identifiable in the western area. However, elements of this fauna are found in the Williamsville bioherm and in the biostrome at Mud Creek (Canandaigua quad.).

Nedrow Member

Zones D and E, as defined above for the central area, are unrecognizable west of the Auburn quadrangle (Fig. 1). The westernmost exposure of these two zones is at Auburn, where the *Platyceras* gastropods are rare although the brachiopods and lithology are typical. Between Auburn and Oaks Corners (Phelps quad.) this member is not exposed. Westward from Oaks Corners (Pl. 1) the beds overlying the Edgecliff member represent a completely different facies, with chert forming nearly half the bulk in all localities. Where first seen these beds have a thickness comparable to that of the Nedrow member in the central area (15 feet). They thicken rapidly westward to 45 feet in the Livonia Shaft (interpreted from Luther, 1894, p. 276–281). Elsewhere the thickness is unknown as no other complete exposure of the member has been found. This is the "true cornitiferous" of Hall (1841, p. 158).

The beds have a sparse fauna. Six of 14 localities produced no identifiable fossils. At the others a few specimens were collected, but the same species was not found at more than two localities (Table 2). Only rare specimens were found in the chert. Most species listed for the western Nedrow facies are Edgecliff forms which seem to have survived into lower Nedrow times in this area.

An unusual fauna for this facies was found at Phelps (Phelps quad.). This small fauna (Table 2) contains two common forms, elsewhere recognized only in the upper Moorehouse and Seneca members, and appears to represent an isolated occurrence in early Onondaga times of certain species characteristic of the later Onondaga deposits.

This western Nedrow facies is the least fossiliferous unit of the New York Onondaga. Poor conditions for preservation apparently were coupled with poor living conditions, as fossil fragments indicate a greater variety of forms. Probably rougher water caused the breaking up of most skeletal parts. There is no

chert fauna evident, possibly indicating that this chert is secondary.

Moorehouse Member

The Moorehouse member can be traced west from the central area as far as the Honeoye quadrangle with little faunal or lithological change. Zones F and G are not readily separable, however (Pl. 1). Chert becomes more common in the lower zone, and the faunal distinction breaks down. The chert-gastropod association is entirely lacking and the gastropods do not appear even in the limestone. Except for these forms the fauna is similar to the central area. Zone G elements, except for the chert-gastropod forms, are distributed through the whole member (Pl. 1, brachiopod facies).

Farther west the member is represented by a coral facies. The limestone is coarser and somewhat lighter-colored than that of the central area, and seems to contain fewer impurities. The chert is similar but more evenly distributed throughout the member. The fauna contains numerous corals and brachiopods. At Stafford and Leroy (Batavia and Caledonia quads.) there is a 1-foot bed of limestone and chert in equal amounts, made up almost entirely of the skeletons of two colonial rugose corals, *Cylindrophyllum* and *Synaptophyllum*. The former has been found only in this facies. The westward extension of the 1-foot bed is not known. At these two localities most of the other corals are immediately above and below this bed; brachiopods dominate lower in the member and evidently represent the brachiopod facies. Farther west at Bowmansville (Depew quad.) corals are distributed throughout the member.

The upper part of the Moorehouse, especially in the brachiopod facies, is characterized by the common occurrence of *Pholidostrophia nacrea* (Pl. 1). This has been found at the same horizon in the coral facies but is not common.

The full thickness of the Moorehouse is nowhere exposed, but Luther's (1894, p. 240–241) Livonia Shaft section shows it to be approximately 65 feet. Surface exposures indicate a minimum of 50 feet over the western area, and thinning toward the central area where it is only 25 feet thick.

The ecologic situation in the western area in Moorehouse times was similar to the central area. Benthonic conditions were good, and most types were well represented. Clearer, more agitated water is indicated by the lithology of the western (coral) facies. Under these conditions some of the solitary rugose and tabulate corals, which had characterized Edgecliff times, returned and mingled with the Moorehouse brachiopods without, however, resuming their former dominant position.

Seneca Member

The Seneca member as defined for the central area can be recognized as far west as Canandaigua Lake (Canandaigua quad.). Here is the westernmost known surface exposure of the Pink *Chonetes* zone (J). Luther (1894, p. 240) indicates the presence of the bentonite bed at Livonia (Honeoye quad.), but the fauna is only generally discussed. Although *Chonetes lineatus* is present, no mention is made of the *Chonetes* zone. Professor Newton E. Chute and Mr. Malik Robinson, both of Syracuse University, have located the bentonite in a quarry near Buffalo (Chute, personal communication). Faunal studies have not been made to determine the character of the Seneca member in this area.

The exposure north of Canandaigua Lake shows the same zonal sequence as the central area. The concentration of *C. lineatus* is not so great, however, and there is every indication that the Seneca is here grading westward into a different facies. *Chonostrophia reversa* maintains its position in zone K, but the bed of *Heterophrentis* sp. B is absent. The upper part of K and L are missing, but the Marcellus contact at Livonia is abrupt (Luther, 1894, p. 239–240). In the Livonia shaft the Seneca is 21 feet thick according to Luther's placing of the bentonite bed.

West of Livonia the Seneca equivalent has been recognized only by its nearness to the Marcellus. Two exposures in the Caledonia quadrangle show the Marcellus contact and might by their positions be referred to zones K and L. They represent different depositional conditions, however. They bear a much larger fauna, contain more chert, and are not dark. No transitional zone from the Onondaga to the Marcellus has been noted. The contact is

TABLE 2.—FAUNA OF WESTERN NEW YORK SECTION

EDGECLIFF MEMBER

ZONE C (BIOSTROME)

Codaster pyramidatus	vr	*Stromatoporoid*	vr
Favosites basalticus	c	Bryozoa spp.	x
F. canadensis	r		
F. emmonsi	x	*Pentamerella arata*	vr
F. epidermatus	vr	*Camarotoechia* sp.	vr
F. tuberosa	vr	*Atrypa reticularis*	x
F. turbinatus	x	*"Spirifer" raricosta*	r
Pleurodictyum convexum	vr	*Ambocoelia umbonata*	vr
P. cylindricum	vr	*Meristella nasuta*	r
Aulopora sp.	vr	*Pentagonia unisulcata*	vr
Romingeria sp.	vr	*Stropheodonta inequiradiata*	vr
Syringopora sp.	r	*Leptostrophia perplana*	?
		Leptaena rhomboidalis	c
Amplexiphyllum hamiltoniae	vr	*Schuchertella pandora*	c
Heterophrentis prolifica	vc	*Levenia lenticularis*	r
H. sp.	c	*Rhipidomella* sp.	vr
Siphonophrentis gigantea	r	*Centronella glansfagea*	vr
Breviphrentis yandelli	vr		
Bethanyphyllum robustum	vc	*Platyostoma lineata*	vr
Blothrophyllum promissum	x	*P. turbinata*	vr
Heliophyllum halli?	r	*Platyceras erectum*	vr
Synaptophyllum simcoense	c	*P.* sp.	vr
Eridophyllum sp.	vr		
Cystiphylloides americanum	vc	*Phacops cristata*	x
C. cf. *conifollis*	c		
C. sulcatum	vr		
C. sp.	r		

ZONE C′ (BIOHERM—WILLIAMSVILLE)

Favosites basalticus	x	*Stromatoporoid* sp.	c
F. canadensis	r	*Caunopora* sp.	x
F. emmonsi	x		
F. epidermatus	r	Bryozoa spp.	c
F. tuberosa	x	*Fenestella* sp.	c
F. turbinatus	x		
Coenites sp.	c	*Pentamerella arata*	r
Pleurodictyum convexum	r	*Elytha fimbriata*	r
P. cylindricum	r	*"Spirifer" duodenarius*	r
Syringopora sp.	c	*Meristella nasuta*	r
		Megastrophia hemisphaerica	r
Heterophrentis sp.	x	*Stropheodonta inequiradiata*	r
Siphonophrentis gigantea	r	*Levenia lenticularis*	r
Bethanyphyllum robustum	vc		
Heliophylloides corniculum	r	*Conocardium* sp.	r
Blothrophyllum decorticatum	r		
B. promissum	r	*Platyostoma lineata*	vc
Heliophyllum gemmatum	c	*P. turbinata*	x
Heliophyllum sp. C	r	*Platyceras argo*	r
Billingsastraea cf. *verneuili*	r	*P. dumosum* var. *rarispinum*	x
Synaptophyllum simcoense	vc	*P. erectum*	r
Eridophyllum gigas	c	*P.* sp.	r
Cystiphylloides americanum	vc	*Orthonychia concavum*	r

TABLE 2.—(*Continued*)

C. sp. A	x		
Chonophyllum magnificum	r	*Phacops cristata*	r
NEDROW MEMBER*			
Favosites basalticus (1)		*Coelospira camilla* (2)	
Aulopora sp. (1)		*Schuchertella pandora* (1)	
		Choneles mucronatus (1)	
Heterophrentis prolifica (2)		*Levenia lenticularis* (1)	
H. sp. (1)			
Siphonophrentis gigantea (2)		*Platyostoma turbinata* (1)	
Bethanyphyllum robustum (1)			
Synaptophyllum simcoense (1)		Ostracod spp. (1)	
Cystiphylloides sp. (1)			
PHELPS FAUNA (SENECA AFFINITIES)			
Lingula palaeformis	vr	*Meristella* ? sp. A**	c
Atrypa reticularis	vr	*Schuchertella pandora*	vr
Anoplotheca acutiplicata	c	*Chonostrophia reversa*†	c
MOOREHOUSE MEMBER			
BRACHIOPOD FACIES			
Aulopora sp.	vr	*Athyris spiriferoides*	r
Ceratopora sp.	r	*Megastrophia concava*	r
		Cymostrophia patersoni	r
Amplexiphyllum hamiltoniae	x	*Strophеodonta demissa*	r
Heterophrentis sp. A	vr	*S. inequiradiata*	r
H. sp. B	x	*Leptostrophia perplana*	c
H. sp. C	vc	*Pholidostrophia nacrea* (upper part only)	c
Heliophyllum sp. A	vr	*Leptaena rhomboidalis*	x
Synaptophyllum simcoense	vr	*Schuchertella pandora*	c
		Chonetes deflectus	x
Bryozoa spp.	x	*C. mucronatus*	vc
Fenestella sp.	r	*Productella navicella*	r
		Strophalosia ? sp.	x
Lingula desiderata	r	*Levenia lenticularis*	vc
L. sp.	vr	*Rhipidomella* sp.	vr
"*Discina*" *minuta*	vr	*Isorthis propinqua*	r
Pentamerella arata	vr	*Centronella glansfagea*	vr
Camarotoechia billingsi	r	*Cypricardella* sp. A.	vr
C. tethys	vr		
Atrypa reticularis	vc	*Euomphalus* cf. *clymenioides*	vr
A. spinosa	vr	*Platyostoma lineata*	x
Coelospira camilla	c	*P. turbinata*	vr
Anoplotheca acutiplicata	x		
Elytha fimbriata	c	*Styliolina fissurella*	vr
Fimbrispirifer divaricata	vr		
"*Spirifer*" *duodenarius*	r	*Goldringia trivolvis*	r
"*Sp.*" *raricosta*	r	Breviconic cephalopod	vr
Ambocoelia umbonata	vr		
Nucleospira concinna	r	*Echinolichas eriopis*	vr
Meristella doris	x	*Phacops cristata*	x

* Species uncommon or rare; number in parentheses indicates number of localities at which species was found, out of 14 localities where collections were made.

** Elsewhere limited to upper Moorehouse and Seneca

† Elsewhere limited to Seneca

TABLE 2.—(*Continued*)

M. nasuta	r	*Odontocephalus selenurus*	r
M. sp.	vr		
Pentagonia unisulcata	vr	Ostracod spp.	x

WESTERN (CORAL) FACIES

Arachnocrinus bulbosus	vr	*"Spirifer" duodenarius*	r
		"Sp." grieri	vr
Favosites basalticus	x	*"Sp." macer*	vr
F. canadensis	vr	*"Sp." raricosta*	vr
F. emmonsi	r	*"Sp." varicosa* (upper part only)	c
F. turbinatus	x	*Meristella doris*	vr
Coenites sp.	x	*M. nasuta*	vr
Syringopora sp.	vr	*M.* sp.	vr
		Athyris spiriferoides	vr
Amplexiphyllum hamiltoniae	r	*Pentagonia unisulcata*	vr
Heterophrentis prolifica	c	*Megastrophia concava*	vr
H. sp. A	vr	*M. hemisphaerica*	vr
H. sp. B	vr	*Stropheodonta demissa*	vr
H. sp.	x	*S. inequiradiata*	x
Siphonophrentis gigantea	r	*Leptostrophia perplana*	c
Breviphrentis yandelli	x	*Pholidostrophia nacrea* (upper part only)	x
Bethanyphyllum robustum	x	*Leptaena rhomboidalis*	r
Blothrophyllum promissum	vr	*Schuchertella pandora*	c
Heliophyllum sp. A	vr	*Chonetes deflectus*	vr
Cylindrophyllum elongatum	vc	*C. mucronatus*	c
Synaptophyllum simcoense	vc	*Productella navicella*	vr
Cystiphylloides americanum	r	*Levenia lenticularis*	c
C. sulcatum	vr	*Isorthis propinqua*	r
		Amphigenia elongata	r
Bryozoa spp.	c		
		"Pleurotomaria" delicatula	vr
Camarotoechia tethys	vr	*"P."* sp.	vr
Pentamerella arata	vr	*Euomphalus decewi*	vr
Atrypa reticularis	vc		
A. spinosa	r	*"Orthoceras"* sp.	vr
Coelospira camilla	x	*Goldringia trivolvis*	vr
Paraspirifer acuminatus	r		
Elytha fimbriata	x	*Phacops cristata*	r
		Odontocephalus selenurus	x

SENECA MEMBER

CENTRAL FACIES

ZONE I

Heterophrentis sp. B	r	*Athyris spiriferoides*	r
		Leptostrophia perplana	r
Lingula sp.	r	*Leptaena rhomboidalis*	x
Pentamerella arata	r	*Schuchertella pandora*	c
Camarotoechia tethys	r	*Chonetes deflectus*	r
Atrypa reticularis	vc	*C. mucronatus*	c
A. spinosa	x	*Levenia lenticularis*	c
Coelospira camilla	c	*Isorthis propinqua*	r
Anoplotheca acutiplicata	r		
"Spirifer" duodenarius	r	*Coleolus crenatocinctum*	r
Pentagonia unisulcata	r		
		Fish teeth	x

TABLE 2.—(*Continued*)

	ZONE J (PINK *Chonetes* ZONE)		
Camarotoechia tethys	r	*Athyris spiriferoides*	r
Atrypa reticularis	x	*Schuchertella pandora*	c
A. spinosa	c	*Chonetes lineatus*	vc
Coelospira camilla	c	*C. mucronatus*	c
Anoplotheca acutiplicata	r	*Levenia lenticularis*	c
Elytha fimbriata	r		
"Spirifer" duodenarius	r	*Odontocephalus selenurus*	r
Meristella nasuta	r		
Pentagonia unisulcata	x	Fish teeth	r
	ZONE K		
Ceratopora sp.	r	*S. inequiradiata*	r
		Leptaena rhomboidalis	c
Lingula sp.	r	*Chonostrophia reversa*	c
Camarotoechia tethys	x	*Chonetes mucronatus*	c
Atrypa reticularis	c	*Levenia lenticularis*	vc
A. spinosa	x		
Coelospira camilla	c	*Platyostoma lineata*	r
Meristella doris	r	*Platyceras carinatum*	r
Stropheodonta demissa	r		
		Odontocephalus selenurus	r
	WESTERN FACIES		
Romingeria sp.	vr	*Stropheodonta demissa*	r
Ceratopora sp.	r	*S. inequiradiata*	vr
		Leptostrophia perplana	vr
Bryozoa sp.	vr	*Leptaena rhomboidalis*	vc
		Schuchertella pandora	r
Pentamerella arata	r	*Chonetes deflectus*	c
Camarotoechia billingsi	vr	*C. mucronatus*	c
Atrypa reticularis	vc	*Levenia lenticularis*	c
A. spinosa	c	*Isorthis propinqua*	r
Coelospira camilla	c		
Elytha fimbriata	vr	*Platyostoma lineata*	x
"Spirifer" duodenarius	c	*Platyceras carinatum*	x
"Sp." varicosa	r		
Meristella nasuta	vr	*Phacops cristata*	x
Strophonella ampla	vr	*Odontocephalus selenurus*	x

fairly well exposed in the creek bed at Leroy. West of the Caledonia quadrangle, no known Seneca has been observed.

Ecologically, conditions during Seneca time improved toward the west and were similar to those of the Moorehouse member.

Faunal Succession

Table 2 lists the complete western area fauna identified by the author from each of the members and zones.

EASTERN NEW YORK SECTION

Edgecliff Member

The Edgecliff is developed throughout the eastern area. It is typically a light-gray, massively bedded, coarsely crystalline limestone which is a coral biostrome at least in its lower part. At most exposures there are scattered nodules of light-gray chert in the upper part. Zone A, the Springvale horizon, is not found east of the Winfield quadrangle, and the Onondaga is generally transitional below into the Schoharie grit.

The Edgecliff thickens eastward. It is 20 feet thick at Springfield Four Corners (Richfield Springs quad.), where the biostrome extends to the top of the member. In the Berne and Albany quadrangles Digman (personal communication) reports a thickness of 39 feet to the top of the light-gray chert. The biostrome occupies only the lower 16 feet, but since the lithology and fauna are identical to that of the central area the entire 39 feet is tentatively referred to the Edgecliff (Pl. 1).

In the Berne, Albany, and Coxsackie quadrangles there are several bioherms similar to the one at Williamsville in the western area. Goldring (1935, p. 144; 1943, p. 231) mentions two, one at the south end of Thompson Lakes (Berne quad.) and one just south of the Albany quadrangle. Digman directed the author to two others, one north of Thompsons Lake and another in the Albany quadrangle just east of Thacher Park. These structures may be seen in limited exposures only, as no quarries have been opened in them. The size of the bioherms is unknown; only 15- to 25-foot thicknesses are exposed. The fauna (Table 3) is remarkably similar to the Williamsville fauna, although much smaller and less representative because of the poorer exposures. Colonial rugose corals predominate, but solitary forms and tabulates are common also. The absence of brachiopods and gastropods may indicate the exposure is well within the "reef" itself and not marginal, as it apparently is at Williamsville.

Edgecliff times in the eastern area were marked by the same conditions prevalent in the central and western areas. Clean, well-agitated waters with "forests" of corals spread over the sea bottom.

Middle and Upper Onondaga

The easternmost known exposure of zone D (the *Platyceras* zone) is at Perryville Falls (Chittenango quad.). Farther east, at Stockbridge Falls (Morrisville quad.) the fauna can be recognized by other elements, but at Springfield Four Corners (Richfield Springs quad.) the Nedrow interval bears a sparse fauna of species found in both the Nedrow and Moorehouse members of the central area. Although faunally indistinctive the shaly nature of the interval is recognizable as far east as Cherry Valley (Canajoharie quad.).

The Moorehouse member is recognizable as far east as Babcock Hill (Winfield quad.). A small quarry near the village shows the lithology and fauna characteristic of zone G in the central area, except for the lack of the chert gastropod association. Eighteen feet is exposed in the quarry, but the top of the member is not seen. Farther east, at Springfield Four Corners, the member cannot be differentiated from the Nedrow, and both members are similar to the central Moorehouse.

The easternmost exposure of the Seneca is at Cherry Valley, where a section from the clay zone (H) up to the Cherry Valley limestone was assembled through coring and exposure. The uppermost part of the Onondaga has not been observed between Cherry Valley and the Schoharie quadrangle, 20 miles farther east where no Seneca is recognized.

Except for the chert, the whole Onondaga formation in the Berne and Albany quadrangles is lithologically similar to the central area biostrome. Throughout, it is a light- or medium-gray, coarsely crystalline limestone. The upper part is slightly darker than the lower and contains dark chert (Pl. 1). The formation above the Edgecliff is not faunally subdivided, and no individual equivalence of the Nedrow or Moorehouse members has been demonstrated.

The upper Nedrow and lower Moorehouse contain apparently barren dark chert in the central area. Presumably the middle cherty layers of the eastern upper Onondaga are lithologically equivalent to these beds, but there is no indication of a time equivalence. Black chert deposition began earliest in the western Nedrow facies where it immediately followed and even interfingered with the light chert beds. It reached the central area in late Nedrow time and began somewhat later in more easterly areas.

The fauna of the eastern upper Onondaga facies is essentially the same below, in, and above the middle dark chert beds. No fossils were noted in the chert itself. Tabulate and rugose corals are common, and in this respect, as well as lithologically, the unit is similar to the western (coral) facies of the Moorehouse member. These corals are primarily Edgecliff

TABLE 3.—FAUNA OF EASTERN NEW YORK SECTION

EDGECLIFF MEMBER

ZONE C (BIOSTROME)

Favosites basalticus	c	*Pentamerella arata*	r
F. emmonsi	r	*Atrypa reticularis*	x
F. epidermatus	r	*"Spirifer" duodenarius*	vr
F. turbinatus	x	*"Sp." raricosta*	x
F. sp.	r	*Ambocoelia umbonata*	vr
Coenites sp.	x	*Meristella* sp.	vr
Ceratopora sp.	r	*Stropheodonta inequiradiata*	vr
Syringopora sp.	r	*Leptostrophia perplana*	vr
		Schuchertella pandora	vr
Heterophrentis prolifica	vc	*Chonetes hemisphericus*	?
H. sp.	x	*Rhipidomella* sp.	vr
Siphonophrentis gigantea	vr		
Breviphrentis yandelli	r	*Platyostoma turbinata*	vr
Bethanyphyllum robustum	vc	*P. erectum*	vr
B. sp.	x		
Blothrophyllum promissum	r	*Proetus clarus*	vr
Heliophyllum sp.	r	*Phacops cristata*	vr
Synaptophyllum simcoense	vc	*Odontocephalus selenurus*	vr
Cystiphylloides americanum	c		
C. cf. *conifollis*	c		
Fenestella sp.	x		

ZONE C′ (BIOHERM)

Favosites basalticus	c	*Billingsastraea* cf. *verneuili*	r
		Synaptophyllum simcoense	c
Siphonophrentis gigantea	r	*Eridophyllum gigas*	c
Bethanyphyllum sp.	vr	*E.* sp.	vr
Heliophyllum gemmatum	c	*Cystiphylloides americanum*	c
		C. sp.	x

NEDROW EQUIVALENT

RICHFIELD SPRINGS QUADRANGLE

Heterophrentis prolifica	r	*Chonetes mucronatus*	x
H. sp.	c	*Levenia lenticularis*	x
Atrypa reticularis	r	*Styliolina fissurella*	r
Coelospira camilla	r		
Pentagonia unisulcata	r	*Goldringia trivolvis*	x
Strophonella ampla	r		
Schuchertella pandora	r	*Phacops cristata*	r
		Odontocephalus selenurus	r

MOOREHOUSE EQUIVALENT

RICHFIELD SPRINGS QUADRANGLE

Coenites sp.	r	*Stropheodonta inequiradiata*	x
Aulopora sp.	r	*Leptostrophia perplana*	vr
Romingeria sp.	r	*Leptaena rhomboidalis*	x
Ceratopra sp.	c	*Schuchertella pandora*	x
		Chonetes hemisphericus	vr
Amplexiphyllum hamiltoniae	x	*C. lineatus*	vr
Heterophrentis prolifica	x	*C. mucronatus*	x

TABLE 3.—(*Continued*)

H. sp. A	c	*Productella navicella*	vr
H. sp. B	c	*Levenia lenticularis*	vc
Synaptophyllum simcoense	vr	*Rhipidomella* sp.	vr
Bryozoa spp.	x	*Loxonema* sp.	vr
Fenestella sp.	r	*Platyostoma lineata*	r
		Platyceras dumosum	x
Pentamerella arata	vr	*P.* sp.	vr
Camarotoechia sp.	r		
Atrypa reticularis	vc	*Hyolithes* cf. *striatus*	vr
Coelospira camilla	r	*Coleolus crenatocinctum*	?
Anoplotheca acutiplicata	vr	*Styliolina fissurella*	x
Elytha fimbriata	x		
"Spirifer" raricosta	vr	*Striacoceras typum*	vr
Nucleospira concinna	r	*Goldringia trivolvis*	r
Meristella doris	r		
M. sp.	vr	*Phacops cristata*	c
Pentagonia unisulcata	r	*Odontocephalus selenurus*	vc
Athyris spiriferoides	vr		
Strophonella ampla	vr	Ostracod spp.	x
Cymostrophia patersoni	vr		
		Fish teeth	vr

MIDDLE AND UPPER ONONDAGA

SCHOHARIE, BERNE AND ALBANY QUADRANGLES

Favosites basalticus	*	*Meristella nasuta*	*
F. epidermatus	*	*Pentagonia unisulcata*	vr
F. sp.	c	*Athyris spiriferoides*	r
Ceratopora sp.	x	*Megastrophia concava*	x
Syringopora sp.	vr	*M. hemispherica*	*
		Stropheodonta inequiradiata	*
Heterophrentis prolifica	c	*Leptostrophia perplana*	vr
H. sp.	x	*Leptaena rhomboidalis*	x
Bethanyphyllum robustum	x	*Schuchertella pandora*	x
B. sp.	r	*Chonetes mucronatus*	c
Heliophylloides corniculum	vr	*C.* sp.	vr
Synaptophyllum simcoense	r	*Productella navicella*	r
Cystiphylloides sp.	r	*Levenia lenticularis*	c
		Rhipidomella sp.	x
Bryozoa spp.	x	*Isorthis propinqua*	r
Fenestella sp.	x		
		"Pleurotomaria" sp.	vr
Pentamerella arata	x	*Eumphalus decewi*	*
Camarotoechia billingsi	vr	*Platyceras carinatum*	vr
Atrypa reticularis	vc	*P. dumosum* var. *rarispinum*	c
A. spinosa	x		
Coelospira camilla	r	*Proetus clarus*	*
Elytha fimbriata	x	*Phacops cristata*	r
Fimbrispirifer divaricatus	*	*Odontocephalus selenurus*	vr
"Spirifer" duodenarius	c		
"Sp." raricosta	x	*"Gyroceras" paucinodum*	*
"Sp." varicosa	*		

* Reported by Goldring (1935 p. 148) from quarry known to be in this unit.

forms which lived on in later Onondaga time in an environment that was similar, but slightly muddier. The mud-loving heterophrentids, which characterize the upper three members in the central area, are rare in the eastern facies. Brachiopods, more limited in the central area, range through the whole eastern Onondaga. The large, spiny gastropod, *Platyceras dumosum* is characteristic. This form is found in the Edgecliff at Williamsville and in the Nedrow of the central area, but ranges throughout the Onondaga from Richfield Springs east. The Edgecliff and the eastern, undifferentiated upper Onondaga are notably crinoidal, and the association of *P. dumosum* with these units may reflect the symbiotic relationship often described between platyceratids and camerate crinoids (Clarke, 1919, p. 69–70).

Quarries at Richfield Springs and Springfield Four Corners (Richfield Springs quad.) show all but the uppermost Onondaga. The exposed section is lithologically intermediate between the central and more eastern sections. An undifferentiated Nedrow-Moorehouse fauna is represented by the numerous heterophrentids and typical brachiopods, but the eastern *Platyceras dumosum* is also present. Dark chert is common from 10 feet above the Edgecliff to the top of the exposure.

The gradual change from the central to eastern areas is also seen in the Moorehouse exposures at Babcock Hill (Winfield quad.) where a few common eastern brachiopods are found in association with a dominantly central Moorehouse fauna (Table 3). Schoharie quadrangle exposures show some fine-grained limestone (central area lithology) in the upper part of the Onondaga, but the fauna is eastern in aspect.

Ecologic conditions in the eastern Onondaga seas did not vary much after Edgecliff time. No fauna is found in the dark chert, and the fauna of the enclosing limestone beds is the same as that above and below the chert beds. This might indicate a secondary origin for the chert.

The upper beds are darker than the lower beds, indicating early stages of black-mud deposition. The ecologic effect was not great, however, as corals remain common. The Marcellus contact was observed at only two places in the eastern area. In these and in the well core made by the State College of Ceramics, the contact was very abrupt. A few very thin limy bands in the lower inch of the Marcellus were the only indications of a gradational contact. Goldring (1943, p. 243) described a third exposure in Onesquethaw Creek (Albany quad.) where she measured a 3-foot zone of alternating limestone and black shale.

Faunal Succession

Table 3 lists the complete eastern area fauna identified by the author from each of the members and zones.

Marcellus Contact

The relationship of the Onondaga to the overlying Marcellus shale has long been controversial. Clarke (1901, p. 115–121) pointed out the gradational nature of the contact and the westward thinning of the black shales below the Cherry Valley limestone; he considered that the early Marcellus of eastern New York was equivalent to the upper Onondaga of western New York. Cleland (1903, p. 20) indicated a faunal gradation from one to the other. Grabau (1932, p. 424) suggested that the black shales represented the lagoonal facies of the off-shore "Onondaga barrier reefs" which were being deposited at the same time.

Chadwick (1927, p. 160) described a "very distinct erosion surface" at the top of the Onondaga, in the Catskill quadrangle (south of Albany), and stated that it "appears to dispose finally of the theory of 'contemporaneous overlap' by the Marcellus black shale." Cooper (1930, p. 123) suggested that the unconformity was a marginal break as would be expected in the near-shore region. Flower (1936, p. 8; 1939, p. 432–434; 1943, p. 1830) agreed with Cooper about the local nature of the break and cited many paleontological indications of the phase relationship. Most authors who have mentioned the subject agree with the contemporaneous overlap theory.

The evidence cited in literature in favor of an overlap relationship is as follows:

1. Westward thinning of lower Marcellus units: The Cherry Valley-Onondaga interval

(=Union Springs shale) is 160–165 feet at Onesquethaw Creek, Albany quadrangle (Rickard, 1952, p. 514); 80–90 feet in the Berne quadrangle (Rickard, 1952, p. 513); 70 feet at Schoharie, Schoharie quadrangle (Flower, 1936, p. 6); 25–30 feet at Cherry Valley, Richfield Springs quadrangle; 24 feet at Stockbridge Falls, (Morrisville quad.); 10 feet at Marcellus (Skaneateles quad.); 13 feet at Union Springs (Auburn quad.); and 9 feet at Flint Creek (Phelps quad.). No more westerly exposure has been found, but the Cherry Valley cephalopod *Agoniatites expansus* was reported from just above the Onondaga in Genesee County and from the top of the formation in Erie County (Clarke, 1901, p. 120–121). In Erie County, Clarke reported "characteristic" (but unlisted) Cherry Valley brachiopods from the top of the Onondaga.

2. Westward extension: the fauna of the Columbus limestone, which is the phase equivalent of the Onondaga in Ohio, carries a Hamilton fauna in its upper part (Flower, 1943, p. 1830). This suggests a westward rise in time of the Onondaga-Columbus phase.
3. Gradational contact, discussed below.
4. Faunal gradation, discussed below.

The contact is exposed at only a few places. At Leroy (Caledonia quad.) the uppermost Onondaga exposed is 100 feet down-stream but only 2 feet lower than the black Marcellus shale. The uppermost Onondaga is very dark and fine grained, but no other indication of a gradational contact is seen. The uppermost limestone beds exposed bear abundant Onondaga fossils.

The contact in the Livonia Salt Shaft (Honeoye quad.) as described by Luther (1894, p. 239–240) is apparently abrupt, but two dark limestone beds 11 feet above the Onondaga carry a mixed Onondaga-Hamilton fauna.

Cooper (1930, p. 132) mentioned the contact in Flint Creek, southwest of Phelps, and said that the Cherry Valley limestone is 9 feet above the Onondaga. The lower most Marcellus is exposed at this locality, but the presence of the actual Onondaga contact is not positive. Three beds of very dark limestone aggregating 19 inches are found at the base of the section. *Styliolina fissurella* in great numbers, *Coleolus* sp., and *Tentaculites* sp., the only fossils found in the limestone, give a Marcellus aspect to these beds and suggest that they are in the Onondaga-Marcellus gradation zone. An alternation of dark limestone and black shale is present.

The Union Springs section (Auburn quad.), discussed in connection with the upper contact in the central area, represents an alternation of black shale and limestone deposition between the Onondaga and the Cherry Valley limestone. Southeast of Marcellus (Skaneateles quad.) is another exposure of the uppermost Onondaga, Union Springs and Cherry Valley, described previously. The limestone-black shale alternation is well shown.

At Stockbridge Falls (Morrisville quad.) the section extends from the bentonite zone (H) to the Cherry Valley limestone. Black shale with numerous dark limestone beds overlies a few inches of zone K. South of Cherry Valley (Canajoharie quad.) is a complete creek-bed exposure of the Seneca-Union Springs-Cherry Valley sequence. Only the uppermost 3 feet of the Seneca is exposed, but this carries a typical Seneca fauna, and a drill core of the Onondaga, taken by the New York State College of Ceramics, showed the Tioga bentonite just 6 feet below the top of the formation. Here the black shales rest on zone I.

Farther east the contact has been reported only in the Berne-Albany area. Goldring (1935, p. 155) mentions an exposure near the south end of Thompsons Lake (Berne quad.). The contact was seen here and in a well core made by the State College of Ceramics, just east of Thacher Park (Albany quad.). The contact is abrupt in both sections; a few limy bands in the lower inch of black shale in the core mark the only evidence of a transition. This contact is exposed also in Onesquethaw Creek, just north of Wolf Hill where Goldring (1943, p. 243) reported a 3-foot transition zone from the limestone to black shale. South of the capitol area near Catskill the contact was described by Chadwick (1944, p. 103), who believed an unconformity is indicated.

Clearly, ecologic and sedimentary conditions changed gradually from late Onondaga to early Marcellus time. The lithologic transition would be expected to be accompanied by faunal transition. Clarke (1894, p. 350) considered the

faunas from some of the limestone bands of the Union Springs to be Onondaga derivatives. The relationship is further exemplified by the persistence into later Hamilton time of several Ondondaga species or closely related species.

An intimate relationship is indicated by the lithologic and faunal gradation, but the time-plane position of the contact has not been known. The bentonite zone (H) is probably a time plane and, if extended far enough, would provide the answer. Its relation to a known Marcellus horizon has been observed in only three places. At Union Springs the bentonite zone is 37½ feet below the Cherry Valley limestone. Fifty-five miles east at Stockbridge Falls the interval is 36 feet, and 50 miles farther east at Cherry Valley the interval is 33–36 feet. To the east the higher zones of the Union Springs area pass laterally into the black shales. At Stockbridge Falls only a few inches of zone K remains, and at Cherry Valley only zones H and I are seen below the Marcellus. The contact at the three localities is transitional.

The parallelism plus the westward thinning of the Union Springs and eastward thinning of the Seneca indicates the essential equivalence of the Seneca and Union Springs members. The successive eastward disappearance of the Seneca zones is further support for this interpretation. Chadwick's unconformity was correctly interpreted as marginal by Cooper (1930, p. 123). Seneca-Union Springs time was marked by a westward regression of Onondaga conditions followed by, and alternating with, Marcellus black-shale conditions. Exactly parallel conditions existed at the same time in central and western Pennsylvania where the bentonite, 30 feet below the contact in western drill holes, is found at the contact in more eastern holes (Fettke, 1952, p. 2040). Further surface work in New York might show the bentonite in the lower Marcellus in the Schoharie quadrangle or farther east.

Onondaga Fauna

CORALS: Corals are the most important stratigraphic and paleoecologic guides in the Onondaga. Each member or facies is characterized by a particular coral assemblage or by the lack of corals. The Edgecliff member is a coral biostrome over most of the State and is characterized by a profusion of large, individual rugose corals and tabulates. Dominant forms are *Bethanyphyllum*, *Cystiphylloides*, *Heterophrentis prolifica*, and *Favosites*. In contrast, the bioherms are characterized by a profusion of colonial rugose corals, only one of which, *Synaptophyllum*, is common elsewhere in the Onondaga.

Elements of the biostrome fauna, large rugose forms, and tabulates are common in the western (coral) facies of the Moorehouse and in the undifferentiated upper Onondaga of the Schoharie-Berne-Albany area. These two coral faunas, both reminiscent of Edgecliff time, are similar except for the occurrence in the west of *Cylindrophyllum elongatum*, which, in association with *Synaptophyllum simcoense*, forms a 12-inch bed extending at least 12 miles.

The central area Nedrow member, the shaly gastropod facies, is characterized by a low turbinate form of *Heliophyllum halli* and by *Amplexiphyllum hamiltoniae*. These were mud-dwellers, also common in the later, muddy Hamilton seas.

The rest of the Onondaga units, primarily medium to dark, fine-grained limestones, are characterized by heterophrentidlike corals. Two small forms, referred to here as *Heterophrentis* sp. A and B, are common throughout the central section above the shaly gastropod zone, and in the Moorehouse member in the west-central (brachiopod) facies, and in the eastern facies as far east as Richfield Springs. *Heterophrentis prolifica* is common throughout the Onondaga, except in the Seneca and the western (dark-chert) facies of the Nedrow where few fossils are found.

ECHINODERMS: Crinoids were important elements in the Onondaga seas although they do not appear on many of the faunal lists (Tables 1–3). Large stem plates up to three-quarters of an inch in diameter are common in the Edgecliff. The matrix of the Edgecliff is composed of small stem sections, and these dominate the upper Edgecliff at many places. The matrix of the Moorehouse coral facies and the eastern undifferentiated facies is partially crinoidal, and these small stem units are common throughout the formation. Many crinoids have been described from the Onondaga, but

only three calices were found during the present study.

Blastoids are not common, although much of the above stem debris might be attributed to them. Several species have been described from the Williamsville area. In the present study three calices of *Codaster pyramidatus* were found in the Edgecliff in the Canandaigua quadrangle.

BRYOZOANS: Bryozoa are abundant in the Onondaga but will be of little stratigraphic value until they have been studied systematically. Fenestellids are most common in the Edgecliff but are present throughout the formation.

BRACHIOPODS: Brachiopods are the most common fossils in the Onondaga. They are present in all members, zones, and facies, and generally range through more than one stratigraphic unit.

Zone A, the reworked sand zone, is locally characterized by unusually large forms of common Onondaga brachiopods, particularly *Pentamerella arata*. These forms are adapted to the unusual sandy conditions which began Onondagan time. The characteristic Oriskany *Costispirifer arenosus* (=*unica*) in this fauna is of doubtful significance.

Zone B, locally developed at two points in western New York, contains an abundance of *Amphigenia elongate*, *Centronella glansfagea*, and "*Spirifer*" *duodenarius*. The first two occur higher in the formation but are extremely rare farther east. "*Sp.*" *duodenarius* is found over the whole State in all members, but never in comparable numbers.

The Edgecliff proper (Pl. 1, zone C) has a sparse brachiopod fauna, but "*Spirifer*" *raricosta* is present at most outcrops of this unit, though it is nowhere common. It is also in both the eastern and western coral facies of the Moorehouse.

The Nedrow and Moorehouse zones have similar brachiopod faunas. They are separated primarily on coral and gastropod elements and relative abundance of brachiopod individuals. The upper part of the western Moorehouse is characterized by *Pholidostrophia nacrea*, which is found only locally in the Onondaga, but is widespread in the later Hamilton beds.

The Seneca member is dominated by *Chonetes lineatus*, which is scarce elsewhere. *Chonostrophia reversa* is characteristic of the upper part of the member. Most Nedrow and Moorehouse forms are not found in the Seneca, but a few are common, and several are found locally near the western extremity of the member.

MOLLUSKS: Gastropods are stratigraphically significant in the Onondaga. Two interesting faunal associations, the shaly platyceratid fauna of the lower Nedrow, and the cherty gastropod fauna of the upper Moorehouse and lower Seneca, are limited to the central area.

A parasitic or symbiotic relationship between platyceratids and camerate crinoids has been frequently mentioned in literature (Keyes, 1889; Clarke, 1919, p. 69–70). The distribution of these forms in the Onondaga does not suggest that the relationship was universal, as crinoidal debris is not common in zone D (the *Platyceras* zone). However, *P. erectum* and *P. dumosum* have been described in association with crinoids (Clarke, 1919; Wells, 1947, p. 120), and these two species are generally found in the Edgecliff or eastern undifferentiated facies of the Onondaga, both notably crinoidal.

Of the chert associates, only the "pteropod" *Coleolus crenatocinctum* is common in the limestone. It is found throughout the Moorehouse and lower Seneca members in the central area, but is uncommon farther east or west. *Styliolina fissurella* is common locally in the Moorehouse, but was not noted in the Seneca although it is extremely abundant in the overlying Marcellus.

Cephalopods are not common, but are of considerable importance. *Halloceras undulatum* is characteristic of the central Moorehouse although found in the Nedrow as well. At the type locality of the Moorehouse dozens of specimens were found on one broadly exposed bedding plane (Fig. 2). In the eastern and western Moorehouse, *H. undulatum* is seemingly replaced by *Goldringia trivolvis*. These two gyrocones have not been found associated with each other. Several brevicones and orthocones have been found in the Moorehouse member, but few are identifiable.

Pelecypods are uncommon, and only a few forms have been found in the present study. *Conocardium* sp. has been noted in the Williamsville bioherm and in one of the eastern bioherms and is perhaps a characteristic reef or near-reef type.

ARTHROPODS: Trilobite fragments are com-

mon in most zones, but even semicomplete specimens are rare. Only two species, *Phacops cristata* and *Odontocephalus selenurus*, are common, although many others have been described from the formation. Both the common forms are found throughout the Onondaga, but *P. cristata* is rare in the Seneca member.

Ostracods are common in the Onondaga and have been noted in most zones. They are probably of considerable stratigraphic importance but have not been studied here.

VERTEBRATES: Numerous fish teeth and plates have been described from the Onondaga. Hall (1879, p. 140) mentioned a "bone bed" at the top of the Onondaga, and several museum specimens are crowded with fish teeth, but no such deposit has been seen in the field. Several individual teeth have been found, mostly referable to *Onychodus sigmoides*.

LIMESTONE MICROFAUNA: Some additions to the faunal lists were made by dissolving the limestone in a solution of one part glacial acetic acid and two parts water. Insufficient work was done to determine distribution patterns on these forms, but their presence is of interest. The following were found in the Moorehouse member:

Sponge spicules	
Astraeospongia sp.	vc
Ensiferites sp.	c
Hindia? sp.	x
unidentified spicules	
hexaxial	x
triaxial	vr
monaxial	r
Bryozoan fragments	x
Gastropod protoconchs	x
Conodonts	c
Fish teeth	r

ORIGIN OF CHERT

The nature and distribution of the chert has been described for each stratigraphic unit. The chert may be considered in three categories; the dark chert with associated gastropod fauna, the barren dark chert, and the barren light-gray chert.

The chert-gastropod association is characteristic of the central area Moorehouse and lower Seneca members. In addition to the gastropods there is evidence of a considerable microfauna. White (1862) described sponge spicules and diatoms from the Onondaga chert, but localities or horizons are not known. Schneider (1894, p. 29) mentioned the same in Onondaga County, probably from these members, and stated that the nodules were formed from the remains of these organisms. Grabau (1932, p. 424) ascribed the origin of the chert to the same agency. Baschnagel (1942) described an algal flora from the chert. Most of Baschnagel's localities appear to be in the beds under discussion. Traces of these microfossils can be seen on fracture surfaces of the chert, but thin sectioning is necessary for identification.

The special chert fauna is a clear indication of certain siliceous conditions in the sea water in which the animals lived. It is not believed that the silica nodules were actually deposited on the sea bottom, but that the presence of silica in the water from some terrestrial source permitted the "bloom" of siliceous micro-organisms and provided the specialized conditions in which the gastropods thrived. Laird (1935, p. 289) suggested that organic decay started the precipitation of colloidal silica soon after burial and that lithification of the chert and limestone were roughly contemporaneous.

The rest of the chert is not known to bear any special fauna. In the western area especially, the biostrome corals are found partially in the limestone and partially in the light chert. The chert has evidently replaced the limestone. Microscopic structures observed by Laird in Ontario indicate that the chert beds formed after deposition, but before consolidation of the limestone. The facies relationship of the Edgecliff (light chert) and Nedrow (dark chert) in the western area indicates that the type of chert is intimately connected with the limestone lithology. The eastward stratigraphic rise of the dark chert and the consequent thickening of the noncherty interval is further indication that the causative agent existed during rather than after deposition of the enclosing limestone.

The dark color of the upper chert is due to an excess of carbonaceous matter (Laird, 1935, p. 271). If the chert were formed soon after deposition, carbonaceous impurities might be concentrated with the silica. The light-colored

Edgecliff member contains little carbonaceous matter and consequently has light-colored chert.

The actual origin of the chert remains an open question. Possibly it is related to volcanic activity, the erosion of fresh volcanic tuffs providing the silica which became segregated as chert, either directly as replacement or indirectly through organic agency.

Summary and Conclusions

The Onondaga formation in New York consists of several lithologic and faunal units which partially represent sequential developments through Onondaga time and partially lateral variations in conditions. The faunas are facies, rather than time developments, and each represents a particular environment, which is reflected in the lithology. Many of the species, whose distribution is restricted in the Onondaga, appeared first in the Schoharie formation or reappear later in the Hamilton group. During Onondaga time they were confined by the geographical extent and duration of the particular environment in which they could successfully compete. Exceptions are the *Cylindrophyllum-Synaptophyllum* bed and the Pink *Chonetes* zone (J), which probably represent time developments of great horizontal and slight vertical extent. These forms are not found in comparable numbers elsewhere in the Onondaga, even where similar conditions must have existed.

Onondaga deposition succeeded Schoharie deposition in eastern New York with no apparent break, but advanced over an erosion surface in central and western parts of the State. Black-shale deposition followed Onondaga time and began earlier in the east than in the west. The Union Springs and Cherry Valley members of the Marcellus are time equivalents of the Seneca limestone farther west.

Superimposed on the general east to west changes is a similarity between the eastern and western areas in thickness, lithology, and fauna. From a thickness of less than 70 feet near Syracuse the Onondaga increases (easterly) to 118 feet near Cherry Valley and (westerly) to nearly 150 feet in the area west of the Livonia salt shaft. Coupled with this is the similarity between the undifferentiated eastern upper Onondaga facies and the western coral facies of the Moorehouse member. Both of these are more coarsely crystalline and somewhat lighter in color than their central equivalents, and both carry coral and crinoid faunal elements reminiscent of Edgecliff time.

The absence of corals and coarsely crystalline limestone in the central area reflects increased argillaceous impurities in the upper three members. Probably slightly deeper water marked the central area in post-Edgecliff time, resulting in a higher relative rate of mud deposition and fewer $CaCO_3$-secreting organisms. The coral faunas thrived in the well-agitated shallower waters while gastropods and brachiopods dominated the muddier central area.

References Cited

Baschnagel, R. A., 1942, Some microfossils from the Onondaga chert of central New York: Buffalo Soc. Nat. Sci. Bull. 17, no. 2, p. 1–8.

Bishop, I. P., 1886, Salt wells of western New York: N. Y. State Geol. Ann. Rept. 5, p. 12–47.

—— 1897, The structural and economic geology of Erie county: N. Y. State Geol. Ann. Rept. 15, p. 309–392.

Chadwick, G. H., 1919, Phelps quadrangle, *in* Clarke, J. M., 1919, Fourteenth Report of the Director of the State Museum and Science Department, N. Y. State Mus. Bull. 207–208, p. 42–43.

—— 1927, New points in New York stratigraphy (Abstract): Geol. Soc. America Bull., v. 38, p. 160.

—— 1944, Geology of the Catskill and Katterskill quadrangles. Pt. 2: N. Y. State Mus. Bull. 336, 251 p.

Clarke, J. M., 1894, The succession of the fossil faunas in the section of the Livonia salt shaft: N. Y. State Mus. Ann. Rept. 47, p. 327–352.

—— 1901, Limestones of central and western New York interbedded with bituminous shales of the Marcellus stage with notes on the nature and origins of their faunas: N. Y. State Mus. Bull. 49, p. 115–138.

—— 1902, The indigene and alien faunas of the New York Devonic: N. Y. State Mus. Bull. 52, p. 664–672.

—— 1919, Organic dependence and diseases: their origin and significance: N. Y. State Mus. Bull. 221–222, p. 1–113.

Cleland, H. F., 1903, A study of the fauna of the Hamilton formation of the Cayuga Lake section in central New York: U. S. Geol. Survey Bull. 206, 112 p.

Conrad, T. A., 1837, First annual report of the geological survey of the third district: N. Y. Geol. Survey Ann. Rept. 1, p. 155–186.

Cooper, G. A., 1930, Stratigraphy of the Hamilton group of New York, pts. 1 and 2: Am. Jour. Sci., 5th ser., vol. 19, p. 116–134, 214–236.

Cooper, G. A., *et al.*, 1942, Correlations of the Devonian sedimentary formations of North America: Geol. Soc. America Bull., v. 53, p. 1729–1794.

Delafield, J., 1850, A general view and agricultural survey of the county of Seneca: N. Y. State Agric. Soc. Trans., v. 10, p. 356–616.

Eaton, Amos, 1828, Geological nomenclature, classes of rocks, etc.: Am. Jour. Sci., v. 14, p. 145–159, 359–368.

Fettke, C. R., 1952, Tioga bentonite in Pennsylvania and adjacent states: Am. Assoc. Petroleum Geologists Bull., v. 36, p. 2038–2040.

Flower, R. H., 1936, Cherry Valley cephalopods: Bull. Am. Paleont., no. 76, 96 p.

—— 1939, Study of the Pseudorthoceratidea: Palaeontographica Americana, v. 2, no. 10, 175 p.

—— 1943, Middle Devonian nautiloids of New York (Abstract): Geol. Soc. America Bull., v. 54, p. 1830.

Flowers, R. W., 1952, Lower Middle Devonian meta-bentonite in West Virginia: Am. Assoc. Petroleum Geologists Bull., v. 36, 2036–2038.

Goldring, W., 1931, Handbook of paleontology for beginners and amateurs: Part 2, the formations: N. Y. State Mus. Handbook 12, 488 p.

—— 1935, Geology of the Berne quadrangle; with a chapter on glacial geology by John H. Cook: N. Y. State Mus. Bull. 303, 238 p.

—— 1943, Geology of the Coxsackie quadrangle, New York: N. Y. State Mus. Bull. 332, 374 p.

Grabau, A. W., 1900, Siluro-Devonic contact in Erie County, New York: Geol. Soc. America Bull., v. 11, p. 347–376.

—— 1903, Paleozoic coral reefs: Geol. Soc. America Bull., v. 14, p. 337–352.

—— 1906, Guide to the geology and paleontology of the Schoharie Valley in eastern New York: N. Y. State Mus. Bull. 92, p. 77–386.

—— 1932, Principles of stratigraphy: 3rd ed., A. G. Seiler, New York, 1185 p.

Hall, J., 1839, Third annual report of the geological survey of the fourth district: N. Y. Geol. Survey Ann. Rept. 2, p. 286–339.

—— 1840, Fourth annual report of the survey of the fourth geological district (of New York): N. Y. Geol. Survey Ann. Rept. 4, p. 389–456.

—— 1841, Fifth annual report of the fourth geological district: N. Y. Geol. Survey Ann. Rept. 5, p. 149–179.

—— 1843, Geology of New York. Part 4, comprising the survey of the fourth geological district, Albany, 683 p.

—— 1867, Descriptions and figures of the fossil brachiopoda of the Upper Helderberg, Hamilton, Portage, and Chemung Groups: N. Y. Geol. Survey, Paleontology, v. 4, 428 p.

—— 1879, The Louisville limestone: N. Y. Geol. Survey, Paleontology, v. 5, part 2, p. 139–141.

Harris, G. D., 1904, The Helderberg invasion of the Manlius: Bull. Am. Paleontology, v. 4, p. 55–77.

Keyes, C. R., 1889, On the attachment of *Platyceras* to palaeocrinoids: Am. Philos. Soc., Proc., v. 25, p. 231–243.

Kindle, E. M., 1913, The unconformity at the base of the Onondaga limestone in New York and its equivalent west of Buffalo: Jour. Geology, v. 21, p. 301–319.

Laird, H. C., 1935, The nature and origin of chert in the Lockport and Onondaga formations of Ontario: Roy. Canadian Inst. Trans. 20, p. 231–304.

Lincoln, D. F., 1895, Report on the structural and economic geology of Seneca County: N. Y. State Mus. Ann. Rept. 48; pt. 2, p. 57–125.

Luther, D. D., 1894, Report on the geology of the Livonia salt shaft: N. Y. State Mus. Ann. Rept. 47, p. 219–324.

—— 1906, Geologic map of the Buffalo quadrangle: N. Y. State Mus. Bull. 99, 29 p.

—— 1909, Geology of the Geneva-Ovid quadrangles: N. Y. State Mus. Bull. 128, 41 p.

—— 1911, Geology of the Honeoye-Wayland quadrangles: N. Y. State Mus. Bull. 152, 29 p.

Mather, W. W., 1843, Geology of New York. Part 1, comprising the geology of the first geological district, Albany, 653 p.

Prosser, C. S., 1893, The thickness of the Devonian and Silurian rocks of central New York: Geol. Soc. America Bull., v 4, p. 91–118.

Rickard, L. V., 1952, The middle Devonian Cherry Valley limestone of eastern New York: Am. Jour. Sci., v. 250, p. 511–522.

Ruedemann, Rudolf, 1930, Geology of the capital district (Albany, Cohoes, Troy and Schenectady quadrangles): N. Y. State Mus. Bull. 285, 218 p.

Schneider, P. F., 1894, Notes on the geology of Onondaga County, N. Y.: Syracuse, Hall and McChesney, 47 p.

Schuchert, C., 1889, A list of the fossils occurring in the Oriskany sandstone of Maryland, New York and Ontario: N. Y. State Mus. Ann. Rept. 42, p. 396–402.

—— 1900, Lower Devonian aspect of the lower Helderberg and Oriskany formations: Geol. Soc. America Bull., v. 11, p. 241–332.

Smith, B., 1929, Influence of erosion intervals on the Manlius-Helderberg series of Onondaga County, New York: N. Y. State Mus. Bull. 281, p. 25–36.

Stauffer, C. R., 1909, The Middle Devonian of Ohio: Ohio Geol. Survey, 4th ser., Bull. 10, 204 p.

—— 1912, Oriskany sandstone of Ontario: Geol. Soc. America Bull., v. 23, p. 371–376.

—— 1913, Geology of the region around Hagersville (Ont.), Int. Geol. Cong. 12, Canada, Guide Book no. 4, p. 82–99.

—— 1915, Stratigraphy of southwestern Ontario: Geol. Survey Canada, Mem. 34, 341 p.

Ulrich, E. O., and Schuchert, C., 1902, Paleozoic seas and barriers in eastern North America: N. Y. State Mus. Bull. 52, p. 633–663.

Vanuxem, L., 1839, Third annual report of the geological survey of the third district: N. Y. Geol. Survey Ann. Rept. 3, p. 241–285.

—— 1840, Fourth annual report of the geological survey of the third district: N. Y. Geol. Survey Ann. Rept. 4, p. 355–383.

—— 1842, Geology of New York. Part 3, comprising the survey of the third geological district: Albany, 306 p.

Weller, S., 1909, Correlation of the Middle and

Upper Devonian and the Mississippian faunas of North America: Jour. Geology, v. 17, p. 257–285.

Wells, J. W., 1944, Fish remains from the Middle Devonian bone beds of the Cincinnati arch region: Palaeontographica Americana, v. 3, no. 16, p. 5–62.

—— 1947, Provisional paleoecological analysis of the Devonian rocks of the Columbus region: Ohio Jour. Sci., v. 47, p. 119–126.

White, M. C., 1862, Discovery of microscopic organism in the siliceous nodules ot the Paleozoic rocks of New York: Am. Jour. Sci., 2nd ser., v. 33, p. 385–386.

Wilmarth, Grace, 1938, Lexicon of geologic names: U. S. Geol. Survey Bull. 896, 2396 p.

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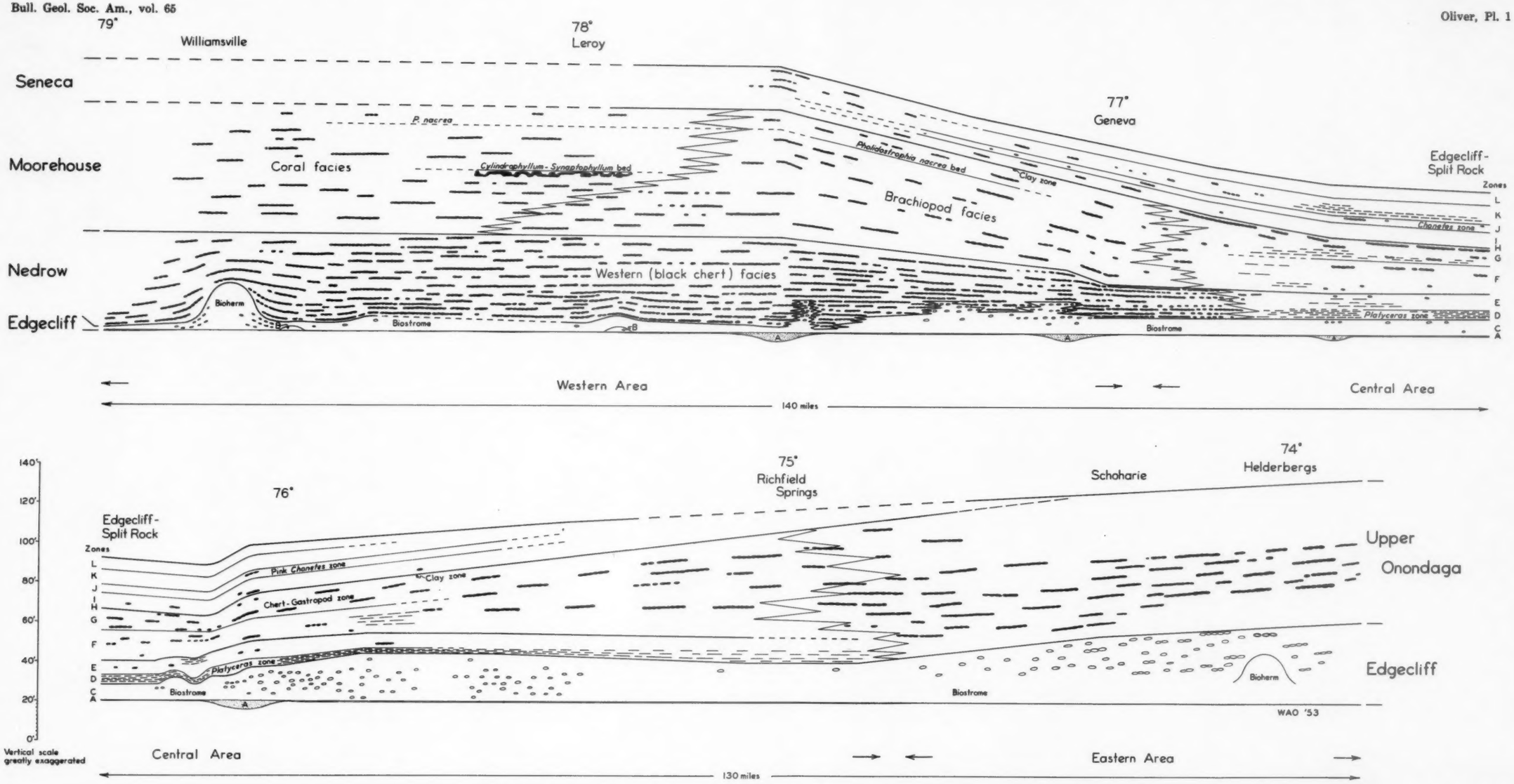

GENERALIZED CROSS SECTION FROM WILLIAMSVILLE TO THE HELDERBERGS

Showing relationships of members, zones, and facies

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GEOPHYSICAL INVESTIGATIONS IN THE EMERGED AND SUBMERGED ATLANTIC COASTAL PLAIN

PART VII. CONTINENTAL SHELF, CONTINENTAL SLOPE, AND CONTINENTAL RISE SOUTH OF NOVA SCOTIA

BY C. B. OFFICER AND M. EWING

ABSTRACT

The results of a series of refraction profiles made over the continental shelf south of Nova Scotia and extending down to the adjacent deep basin are reported. The resulting geologic and crustal sections show the manner in which the gradation from continent to ocean takes place. The Coastal plain sediments reach a maximum thickness of around 20,000 feet on the gently sloping area at the bottom of the continental slope and thin further seaward. The crystalline basement of metamorphic rocks and granites over Nova Scotia gradually thins under the continental margins and pinches out toward the ocean basins. It drops abruptly under the continental slope from 5000 feet to 20,000 feet. The Mohorovičić discontinuity is measured on a single profile at a depth of 52,000 feet under the continental rise.

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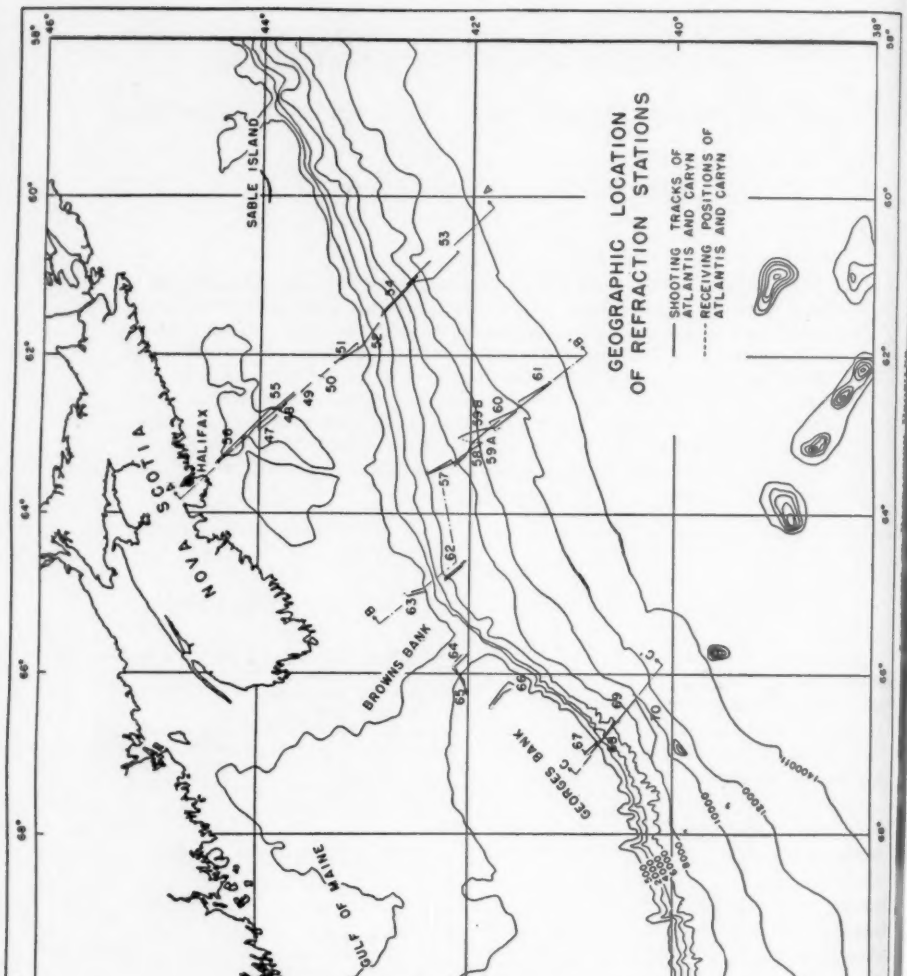
INTRODUCTION

During the summer of 1950 personnel from the Lamont Geological Observatory carried out an extensive deep-sea refraction program. As part of this program a series of profiles were made over the continental shelf from Georges Banks to Sable Island, extending the coverage of known structure of the Atlantic Coastal Plain sediments. In addition, the profile lines were carried out across the continental slope and over the adjacent deep ocean areas (Fig. 1). These data provided three cross sections of the sedimentary and crustal structure on the continental margins.

The geophysical techniques, equipment, and procedures used in these refraction operations have been described previously (Officer *et al.*, 1952, p. 777–783) and will not be repeated here. The methods of analysis were described by Ewing *et al.* (1939, p. 262–270). Continuous


GEOGRAPHIC LOCATION
OF REFRACTION STATIONS
SHOOTING TRACKS OF ATLANTIS AND CARYN
RECEIVING POSITIONS OF ATLANTIS AND CARYN
SABLE ISLAND
NOVA SCOTIA
HALIFAX
BROWNS BANK
GEORGES BANK
GULF OF MAINE
72°
70°
68°
66°
64°
62°
60°
58°
46°
44°
42°
40°
38°

echo-sounder records were taken along the shooting tracks of all the profiles.

Following the definition and usage of others the terms continental shelf, continental slope, and continental rise are defined topographically for this locality as follows. The continental shelf is the very gently sloping (less than ½°) area from landsend to a depth of water of about 500 feet (.15 km). The continental slope is the steeply sloping (2°–5°) area, from 500 to 7000 feet (.15–2.15 km). The continental rise is the gently sloping (about 1°) area from 7000 feet (2.15 km) out to the ocean basin. From Georges Bank west (Fig. 1) these three regions can be easily distinguished; but from Browns Bank to Sable Island the transition between the continental slope and continental rise is more gradual.

Travel-time Data and Geophysical Results

General Discussion

This section is a discussion of the travel-time data from each seismic refraction profile. Its purpose is to indicate the degree of accuracy or uncertainty with which the refraction horizons were determined. In addition there is a discussion of the approximations that had to be taken in the final calculations on some of the less complete profiles and the justification for the particular approximations used. This section should be read in conjunction with the travel-time graphs of Plate I and Tables 1 and 2.

Table 1.—Seismic Velocities

Profile	Unconsolidated sediment (1)		Unconsolidated sediment (2)		Semiconsolidated Sediment		Consolidated Sediment		Basement (Granitic Layer)		Intermediate Layer		P_n	
	Ft/Sec	Km/Sec	Ft/Sec	Km/Sec	Ft/sec	Km/Sec	Ft/Sec	Km/Sec	Ft/Sec	Km/Sec	Ft/Sec	Km/Sec	Ft/Sec	Km/Sec
56	(5410)	(1.65)	....	....	.....	....	....	....	18770	5.72	....	....	....	....
47	5490	1.67	....	....	.....	....	....	....	15050*	4.59	....	....	....	....
55	(5410)	(1.65)	....	....	7430	2.26	....	....	19410	5.92	....	....	....	....
48	(5410)	(1.65)	....	....	9040*	2.76	....	....	16710*	5.10	....	....	....	....
49	5320	1.62	....	....	9080*	2.77	12330*	3.76	18500*	5.64	....	....	....	....
50	5720	1.74	....	....	9040*	2.76	11290*	3.44	18560*	5.66	....	....	....	....
51	5520	1.68	....	....	8140	2.48	12840	3.91	18360*	5.60	....	....	....	....
52	5410	1.65	....	....	9130*	2.78	....	....	17670*	5.39	....	....	....	....
63	5510	1.68	6130	1.87	8520	2.60	....	....	17650	5.38	....	....	....	....
64	(5580)	(1.70)	....	....	9210*	2.81	....	....	16050	4.89	....	....	....	....
65	5570	1.70	....	....	8770	2.67	....	....	15280	4.66	....	....	....	....
66	5690	1.74	....	....	8570	2.61	....	....	16720	5.10	....	....	....	....
67	6030	1.84	....	....	8520	2.60	....	....	16460	5.02	....	....	....	....
54	5910	1.80	....	....	9570	2.92	....	....	16840	5.13	....	....	....	....
53	5770	1.76	....	....	.....	....	....	....	14830	4.52	23190	7.07	....	....
62	(5600)	(1.71)	....	....	(9000)	(2.74)	....	....	16470*	5.02	....	....	....	....
57	5620	1.71	....	....	9220	2.81	....	....	13200	4.02	....	....	....	....
58	5920	1.81	6880*	2.10	9090*	2.77	....	....	13680	4.17	....	....	....	....
59	5690	1.74	6500	1.98	.....	....	....	....	14720	4.49	....	....	....	....
60	(5750)	(1.75)	6400	1.95	.....	....	....	....	(16000)	(4.88)	22680	6.91	....	....
61	(5750)	(1.75)	6350	1.94	.....	....	....	....	18170	5.54	23690	7.22	....	....
68	5580	1.70	6370*	1.94	(9650)	(2.94)	....	....	17460	5.32	....	....	....	....
..	....	....	....	....	.....	....	....	....	16760	5.11	....	....	....	....
69	5720	1.74	6880	2.10	10770	3.28	....	....	16400	5.00	22600	6.89	....	....
70	5500	1.68	(6880)	(2.10)	(10770)	(3.28)	....	....	15680*	4.78	21640*	6.60	27810*	8.48

* Unreversed velocities.
( ) Assumed velocities.

Continental Shelf Profiles

This group consists of profiles 47, 48, 49, 50, 51, 52, 55, 56, 63, 64, 65, 66, and 67. In general

TABLE 2.—THICKNESSES AND DEPTHS OF REFRACTION LAYERS

Profile	Thicknesses										Depths					
	Unconsolidated Sediment				Semiconsolidated Sediment		Consolidated Sediment		Water		Basement (Granitic Layer)		Intermediate Layer		Mohorovičić Discontinuity	
	(1)		(2)													
	Ft	Km	Ft	Km	Ft	Km	Ft	Km	Ft	Km	Ft	Km	Ft	Km	Ft	Km
56 N	50	.02	....	.....	....	....	....	.....	160	.05	210	.06	.....	.....	.....	.....
56 S	(1100)	(.34)	....	.....	5010	1.53	....	.....	700	.21	7020	2.14	.....	.....	.....	.....
47	570	.18	....	.....	....	....	....	.....	790	.24	1370	.42	.....	.....	.....	.....
55 N	480	.15	....	.....	4250	1.30	....	.....	710	.22	5440	1.66	.....	.....	.....	.....
55 S	550	.17	....	.....	4090	1.25	....	.....	290	.09	4930	1.50	.....	.....	.....	.....
48	1190	.36	....	.....	1710	.52	....	.....	600	.18	3500	1.07	.....	.....	.....	.....
49	1500	.46	....	.....	2420	.74	6120	1.87	240	.08	10280	3.13	.....	.....	.....	.....
50	2120	.65	....	.....	1650	.50	5230	1.60	300	.09	9300	2.84	.....	.....	.....	.....
51 N	1250	.38	....	.....	3170	.97	9530	2.91	330	.10	14280	4.35	.....	.....	.....	.....
51 S	2340	.71	....	.....	3280	1.00	(9530)	(2.91)	330	.10	15480	5.08	.....	.....	.....	.....
52	2660	.81	....	.....	6100	1.86	....	.....	260	.08	9020	2.75	.....	.....	.....	.....
63 N	1600	.49	140	.04	5050	1.54	....	.....	350	.11	7130	2.18	.....	.....	.....	.....
63 S	1140	.35	880	.27	4530	1.38	....	.....	400	.12	6960	2.12	.....	.....	.....	.....
64 N	(1710)	(.52)	....	.....	3300	1.01	....	.....	800	.24	5810	1.77	.....	.....	.....	.....
64 S	1710	.52	....	.....	3060	.93	....	.....	840	.26	5600	1.71	.....	.....	.....	.....
65 N	1680	.51	....	.....	5610	1.71	....	.....	490	.15	7770	2.37	.....	.....	.....	.....
65 S	1700	.52	....	.....	4850	1.48	....	.....	290	.09	6840	2.08	.....	.....	.....	.....
66 N	1160	.35	....	.....	4630	1.41	....	.....	250	.08	6050	1.84	.....	.....	.....	.....
66 S	1490	.46	....	.....	4950	1.51	....	.....	320	.10	6770	2.06	.....	.....	.....	.....
67 N	1340	.41	....	.....	3870	1.18	....	.....	200	.06	5410	1.65	.....	.....	.....	.....
67 S	1580	.48	....	.....	3390	1.03	....	.....	670	.20	5630	1.72	.....	.....	.....	.....
54 N	6480	1.97	....	.....	9720	2.96	....	.....	3820	1.16	20000	6.10	.....	.....	.....	.....
54 S	6440	1.96	....	.....	....	....	....	.....	11500	3.51	17900	5.45	.....	.....	.....	.....
53 N	5670	1.73	....	.....	....	....	....	.....	11500	3.51	17200	5.25	36800	11.20	.....	.....
53 S	4140	1.26	....	.....	....	....	....	.....	13030	3.97	17200	5.25	41800	12.75	.....	.....
62	(3500)	(1.07)	....	.....	7380	2.25	....	.....	6920	2.11	17800	5.40	.....	.....	.....	.....
57 N	3080	.94	....	.....	7290	2.22	....	.....	5950	1.81	16300	5.00	.....	.....	.....	.....
57 S	4050	1.23	....	.....	3270	1.00	....	.....	7910	2.41	15200	4.65	.....	.....	.....	.....
58 N	5290	1.61	....	.....	1150	.35	....	.....	7810	2.38	14200	4.35	.....	.....	.....	.....

57 N	3080	.94	....	.....	7290	2.22	....	.....	5950	1.81	16300	5.00	.....	.....	.....	.....
57 S	4050	1.23	....	.....	3270	1.00	....	.....	7910	2.41	15200	4.65	.....	.....	.....	.....
58 N	5290	1.61	....	.....	1150	.35	....	.....	7810	2.38	14200	4.35	.....	.....	.....	.....
58 S	1210	.37	7130	2.17	....	....	....	.....	9660	2.94	18000	5.50	.....	.....	.....	.....
59 N	1850	.57	7330	2.23	....	....	....	.....	9650	2.94	18800	5.75	.....	.....	.....	.....
59 S	270	.08	6720	2.05	....	....	....	.....	11720	3.57	18700	5.70	.....	.....	.....	.....
60 N	1160	.36	(8030)	(2.45)	....	....	....	.....	10880	3.32	20100	6.10	28300	8.65	.....	.....
60 S	200	.06	(8030)	(2.45)	....	....	....	.....	12160	3.71	20400	6.20	28700	8.75	.....	.....
61 N	1070	.33	8650	2.64	....	....	....	.....	12130	3.70	21800	6.65	36300	11.05	.....	.....
61 S	400	.12	9420	2.87	....	....	....	.....	14020	4.27	23800	7.25	33300	10.15	.....	.....
68 N	990	.30	(1000)	(.30)	1040	.32	....	.....	1040	.32	4100	1.25	.....	.....	.....	.....
68 P	1390	.42	(1000)	(.30)	13440	4.10	....	.....	3480	1.06	19300	5.90	.....	.....	.....	.....
68 S	1910	.58	(1000)	(.30)	5760	1.76	....	.....	6520	1.99	15200	4.65	.....	.....	.....	.....
69 N	990	.30	2860	.87	6620	2.02	....	.....	7130	2.17	17600	5.35	26000	7.95	.....	.....
69 S	1340	.41	3820	1.16	5560	1.70	....	.....	9070	2.77	19800	6.05	30700	9.35	.....	.....
70	(1340)	(.41)	(3820)	(1.16)	5260	1.60	....	.....	9100	2.77	19500	5.95	26400	8.05	52200	15.90

( ) Assumed thicknesses.

a rather simple structure is found. It consists of a low-velocity layer (5320–6030 ft/sec, 1.68–1.84 km/sec) termed the unconsolidated sediment, an intermediary-velocity layer (7430–9210 ft/sec, 2.26–2.81 km/sec) termed the semiconsolidated sediment, and a high-velocity layer (15050–19410 ft/sec, 4.59–5.92 km/sec) termed the basement. On profiles 49, 50, and 51 an additional layer of velocity 11,290–12,840 ft/sec (3.44–3.91 km/sec), termed the consolidated sediment was measured between the semiconsolidated sediment and the basement. On profile 63 a second unconsolidated sediment was measured. On none of these profiles was an additional horizon measured below the basement. Profiles 51, 55, 56, 63, 64, 65, 66, and 67 were received in both directions producing reversed profiles; profiles 47, 48, 49, 50, and 52 were unreversed.

Profile 56. This was the longest shelf profile shot; the reverse distance is 53 nautical miles. Shots extended nearly to the end on both halves. At the southern station the shots did not start close enough to measure the unconsolidated and semiconsolidated sediment, and at the northern end the unconsolidated sediment was probably too thin to be detected from the records. In the calculations a velocity of 5410 ft/sec was used for the unconsolidated sediment from the results of profiles 47 and 49, and, from profile 48, a thickness of 1100 feet for the unconsolidated sediment at the southern station, and a velocity of 9049 ft/sec for the semiconsolidated sediment. No break was detected in the basement refraction line on either half of the profile. If 45 nautical miles is taken as the minimum distance at which a break in this refraction line might be detected, a minimum depth of 45,000 feet is calculated for an underlying layer of 25,000 ft/sec.

Profile 47. This profile gave a good one-way determination of the basement from first arrivals and the unconsolidated sediment from second arrivals. The semiconsolidated sediment was not measured and was not included in the depth calculations. The unreversed velocity of 13 010 ft/sec for the basement was the lowest measured. The results of profiles 48, 55, and 56 show that there is a regional dip of the basement seaward from station 47 (Fig. 2). In the calculations this dip was included, giving a true velocity of 15,050 ft/sec, which is still considerably lower than that found on adjacent profiles. Whether this is a real variation in the basement velocity, a change in the overlying formations, or a change in the dip of the basement cannot be answered from this unreversed profile. That this lower horizon is the basement and not an intermediary zone, for instance the consolidated sediment of profiles farther seaward, is inferred from the results of the nearby profiles 48, 55, and 56.

Profile 55. This profile gave a good determination of the basement on both halves and of the semiconsolidated sediment at the southern station. For the northern station the line for the semiconsolidated sediment was drawn through the one measured arrival and the reverse point. The unconsolidated sediment arrivals could not be read from the records; a velocity of 5410 ft/sec from profiles 47 and 49 was used in the calculations.

Profiles 48. This profile gave a good determination of the basement from first arrivals and of the semiconsolidated sediment from second arrivals. The unconsolidated sediment arrivals could not be read from the records. A velocity of 5410 ft/sec for the unconsolidated sediment from profiles 47 and 49 was used in the calculations. The depths and velocities were computed assuming a zero slope of the basement and semiconsolidated sediment.

Profile 49. This profile measured the unconsolidated sediment from four second arrivals, the semiconsolidated sediment from one first arrival, and for the first time the consolidated sediment from three first arrivals. The basement was measured by only one arrival. A velocity of 18,500 ft/sec from profiles 50 and 51 was assumed for the calculation of the depth of the basement. Calculations were made with the assumption of zero slope of the basement, consolidated, and semiconsolidated sediment.

Profile 50. This profile is almost identical with profile 49 but has a slightly better determination of the basement. Calculations were made with the assumption of zero slope of the overlying layers.

Profile 51. This profile gave a good determination of the unconsolidated, semiconsolidated, and consolidated sediment on both halves. The basement was measured only at the northern station. In the calculations the basement was assumed to have zero slope.

Profile 52. This profile gave a good determination of the unconsolidated sediment from second arrivals and the semiconsolidated sediment and basement from first arrivals. The consolidated sediment was not measured and if present is very thin. In the calculations the basement and semi-consolidated sediment were assumed to be horizontal.

Profile 63. This profile gave a good determination of the basement on both halves and with the aid of the reverse points a good determination of the semiconsolidated sediment. At the northern station two unconsolidated sediments were measured; at the southern station only arrivals from the lower sediment could be read with assurance.

Profile 64. This profile was shot along the entrance to the Gulf of Maine at an average depth of water of 820 feet. The basement was well determined on both halves. The semiconsolidated sediment was measured only at the southern station, and the unconsolidated sediment was not measured. In the calculations a velocity of 5580 ft/sec averaged from profiles 65 and 66 was used, and the upper boundary of the semiconsolidated sediment was assumed to have zero slope.

Profile 65. This profile was shot across the entrance to the Gulf of Maine. The northern station was in 488 feet of water, and the southern station in 292 feet. The profile gave a good determination of the basement and unconsolidated sediment on both halves and with the aid of the reverse points a good determination of the semiconsolidated sediment on both halves. The topographic corrections are quite large so that confidence in the results is not as great as on adjacent profiles.

Profile 66. This profile gave a good determination of the basement, semiconsolidated sediment, and unconsolidated sediment on both halves of the profile.

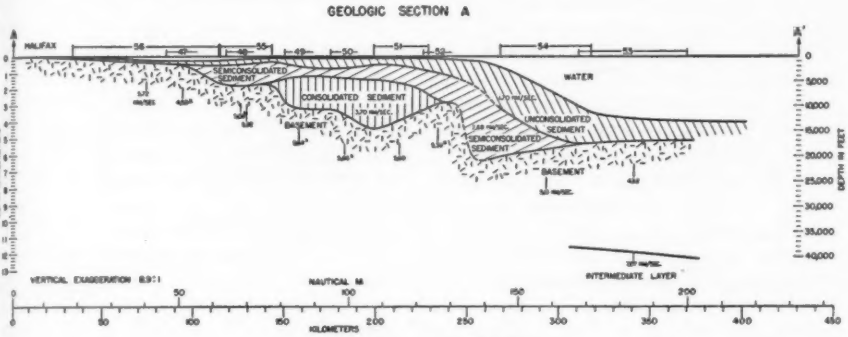


FIGURE 2.—HALIFAX SECTION

Profile 67. This profile also gave a good determination of the basement, semiconsolidated sediment, and unconsolidated sediment.

Continental Slope and Continental Rise Profiles

This group consists of profiles 53, 54, 57, 58, 59, 60, 61, 62, 68, 69, and 70. The area has a more complex structure than the shelf (Figs. 2, 3, 4). A second unconsolidated sediment is measured on profiles 58, 59, 60, 61, 68, 69, and 70. The semiconsolidated sediment is thickest near the bottom of the continental slope and thins and disappears farther seaward; it is not present under profiles 53, 59, 60, and 61.

Below the basement on profiles 53, 60, 61, 69, and 70 a lower crustal layer of velocity 21,640—23,690 ft/sec (6.60–7.22 km/sec) is measured. On profile 70 a third crustal layer with a velocity 27,810 ft/sec (8.48 km/sec) is measured. Except for the lowest crustal horizon Hill (1952) obtains a similar structure on the continental rise west of Ireland. Profiles 53, 54, 57, 58, 59, 60, 61, 68, and 69 were reversed, and profiles 62 and 70 unreversed.

Profile 54. This profile gave a good determination of the basement from first arrivals and of the unconsolidated sediment from second arrivals and the reverse points on both halves. The semiconsolidated sediment was measured

at the northern station only. At the southern station the experimental points show the break from basement to unconsolidated sediment first arrival. Probably there is 1000 feet or less of semiconsolidated sediment under this station, but none was included in the calculations.

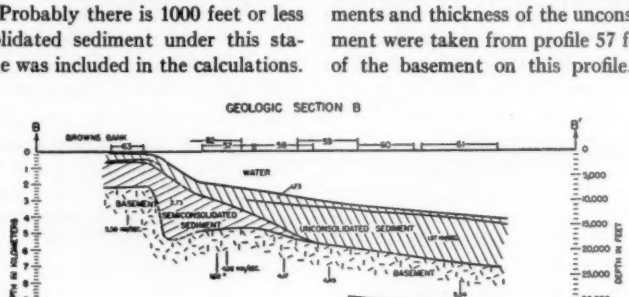


FIGURE 3.—BROWNS BANK SECTION

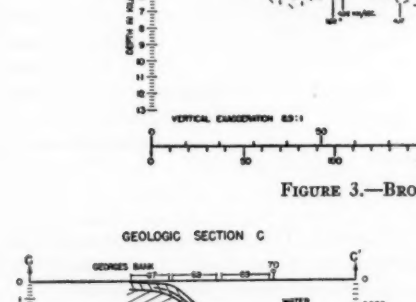


FIGURE 4.—GEORGES BANK SECTION

Profile 53. The unconsolidated sediment was measured from second arrivals at the northern station. The semiconsolidated sediment was not present under this profile, in agreement with the results of the southern station of profile 54. The basement is well determined at the northern station and by the reverse point and two experimental points at the southern station. The second basement is well determined at the southern station and by the reverse point and one experimental point at the northern station.

Profile 62. This profile gave a measure of the basement but not of the unconsolidated or semiconsolidated sediment. Velocities of the unconsolidated and semiconsolidated sediments and thickness of the unconsolidated sediment were taken from profile 57 for calculation of the basement on this profile. This is the poorest profile, and it is included not to add new information but only to show that it is consistent with other profiles in the same geologic locality.

Profile 57. This profile gave a good determination of the unconsolidated sediment, the semiconsolidated sediment, and the basement on both halves.

Profile 58. This profile gave a good determination of the basement. The two unconsolidated sediment layers were measured at the southern station, and, the semiconsolidated sediment layer at the northern station. In the calculations the second unconsolidated sediment was assumed to be parallel to the ocean bottom and to extend under the length of profile 58. As the semiconsolidated sediment was not measured under the southern station, no thickness was included in the calculations for this station.

Profile 59. This profile gave a good determination of the first unconsolidated sediment from second arrivals at the southern station, the second unconsolidated sediment and basement on both halves. In agreement with the results of the southern station of profile 58 the semiconsolidated sediment was not present.

Profile 60. This profile is rather unsatisfactory. It gave a good determination of the second basement and the semiconsolidated sediment

on both halves, but there is no determination of the upper basement or the unconsolidated sediment at either station. In the calculations a velocity of 5750 ft/sec was used for the first unconsolidated sediment from an average of profiles 57, 58, and 59. A thickness of 8030 feet for the second unconsolidated sediment and a velocity of 16,000 ft/sec for the basement from the results of profiles 59 and 61 were assumed to determine the depth of the second basement. The assumed refraction line for the upper basement is drawn on the travel time curve; with the given shot locations this refraction line would not be detected from first arrivals.

Profile 61. This profile gave a good determination of the second unconsolidated sediment, the basement, and the second basement on both halves of the profile. There is a systematic deviation of the points from a straight line for the second basement of the southern station. From the results of profiles 58, 59, and 60 a velocity of 5750 ft/sec for the first unconsolidated sediment was used in the calculations.

Profile 68. This was the only profile that directly measured the drop in the level of the basement at the edge of the continental shelf (Figs. 2, 3, and 4). The downslope of the basement from the northern station is 22° from 4100 feet to 19,300 feet. The apparent basement velocity shooting downslope is 10,710 ft/sec, and that shooting upslope is 65,750 ft/sec; they determine a true velocity of 17,460 ft/sec. It is followed by a more gentle upslope of 5° to 15,200 feet at the southern station. Even over this anomalous section the experimental values from the records, the reverse points, and the observed refraction lines are consistent among themselves as are the calculated velocities and depths.

Profile 69. This profile gave a good determination of the first and second unconsolidated sediments from second arrivals and of the semiconsolidated sediment, the basement, and the second basement from first arrivals and reverse points.

Profile 70. This is the longest profile shot over the continental rise; it extends out to a range of 40 nautical miles. It measured the basement with a velocity of 15,680 ft/sec, the second crustal layer with a velocity of 21,640 ft/sec, and a third crustal layer at a depth of 52,200 feet with a velocity of 27,810 ft/sec. Only this profile measured the third crustal layer. It is possible that the third velocity line represents a change in structure of the overlying formations and not the next lower seismic layer. This cannot be answered from an unreversed profile; but, as the profile was shot along the regional strike, it is doubtful that this line represents a change in structure. The first unconsolidated sediment was determined by second arrivals, and in the calculations velocities for the second unconsolidated sediment and the semiconsolidated sediment and thickness of the two unconsolidated sediments were taken from profile 69.

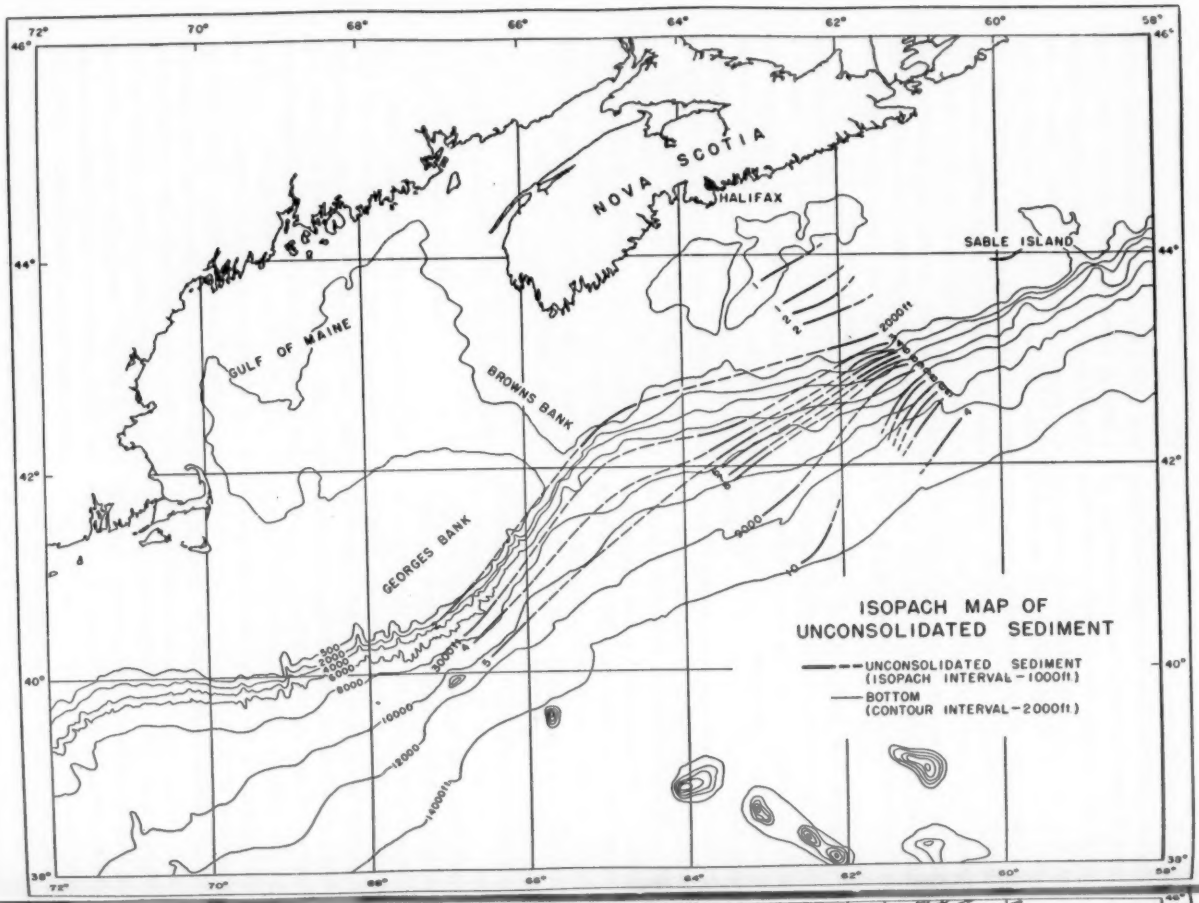
The profiles, both on the continental shelf and the continental slope and rise, present a consistent picture of the regional geology. The three sections across the continental margins show the same structure and the same changes in structure and add weight to the geophysical conclusions that might be drawn from one alone. With exception of No. 62, each of the profiles provides a good determination of its associated refraction layers; the assumptions that had to be made in the calculations on some are justified from the results of nearby profiles.

Identification of Refraction Layers

Sediment Layering

The unconsolidated sediment is present over the whole area (Fig. 5). It is generally less than 2000 feet (.6 km) thick on the continental shelf and reaches a thickness of 10,000 feet (3.0 km) on the continental rise. Along section A (Fig. 2) it thins farther seaward; sections B and C (Figs. 3, 4) did not continue out far enough to indicate this change. Under the deep ocean basin area the unconsolidated sediment is usually less than 2000 feet (.6 km) thick (Officer *et al.*, 1952, p. 791; Tolstoy *et al.*, 1953, p. 35, and Ewing *et al.*, 1954, p. 31). On the continental rise a second horizon is measured in the unconsolidated layer.

The semiconsolidated sediment is present over the outer part of the continental shelf, the continental slope, and the inner part of the continental rise (Fig. 6). It is generally less than 4000 feet (1.2 km) thick on the continental shelf and first appears about 50 nautical miles


NOVA SCOTIA
HALIFAX
SABLE ISLAND
GULF OF MAINE
BROWNS BANK
GEORGES BANK
ISOPACH MAP OF
UNCONSOLIDATED SEDIMENT
UNCONSOLIDATED SEDIMENT
(ISOPACH INTERVAL - 1000ft)
BOTTOM
(CONTOUR INTERVAL - 2000ft)

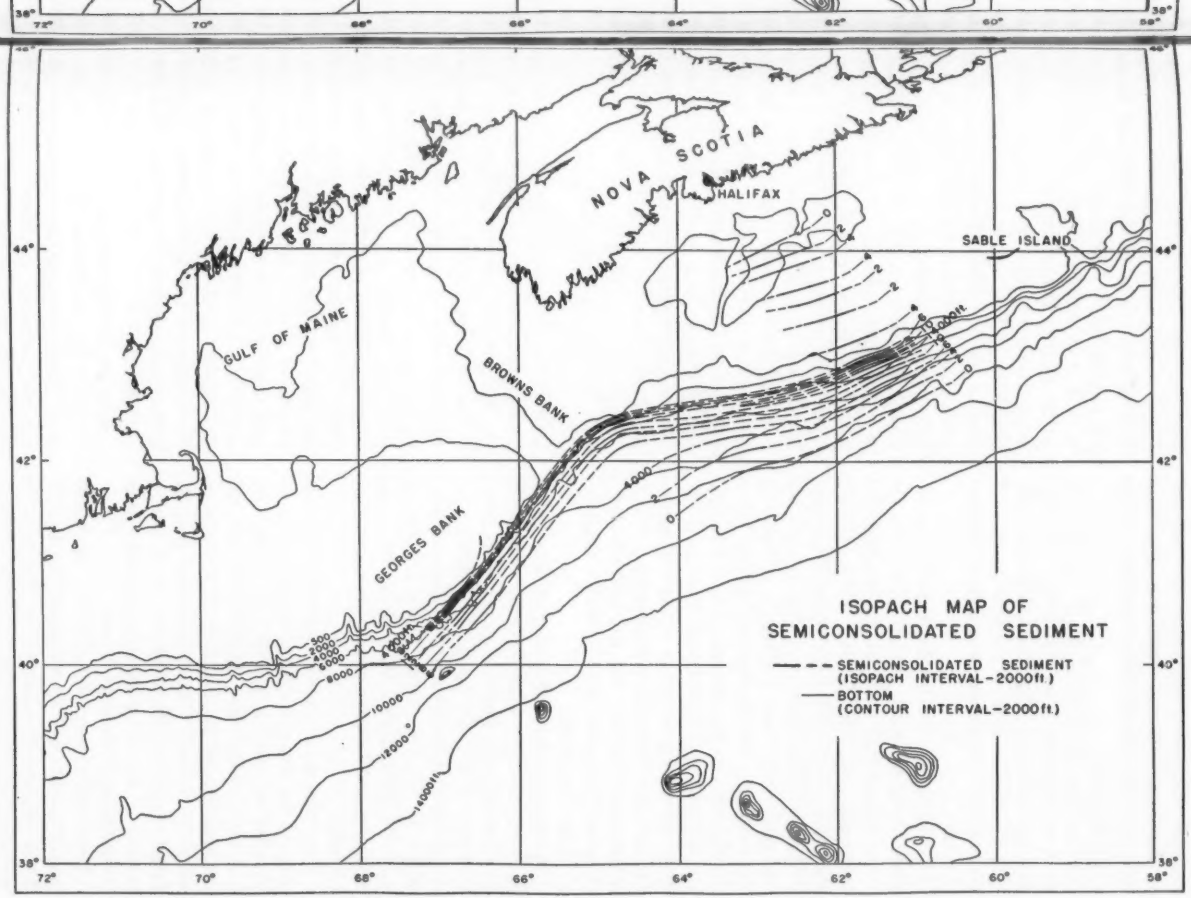


FIGURE 6.—ISOPACH MAP OF SEMICONSOLIDATED SEDIMENT

(90 km) from Halifax. It attains a maximum thickness of 12,000–14,000 feet (3.7–4.3 km) at the bottom of the continental slope and thins and disappears farther seaward on the continental rise.

On profiles 49, 50, and 51 of section A, a lower sedimentary layer was found, the consolidated sediment (Fig. 2). It is present only over this limited area of the continental shelf and reaches a maximum thickness of 9500 feet (2.9 km).

The terms unconsolidated sediment and semiconsolidated sediment are retained from the earlier geophysical work on the emerged and submerged Atlantic Coastal Plain (Ewing *et al.*, 1937; 1939; 1940; 1950; Oliver and Drake, 1951). Where well data or outcrop information was available in these previous investigations, the boundary between the two seismic layers corresponded to the Raritan-Magothy boundary in the Upper Cretaceous. The unconsolidated sediment consisted of Upper Cretaceous, Tertiary, and Quaternary sediments; the semiconsolidated sediment has consisted primarily of Lower Cretaceous with a smaller thickness of Upper Cretaceous.

In another series of offshore refraction profiles in North Carolina (Skeels, 1950), which can be correlated with deep-well data (Swain, 1947; Spangler, 1950), the boundary between the two seismic refraction layers corresponds more nearly to the top of the Upper Cretaceous, with the semiconsolidated sediment consisting of Upper and Lower Cretaceous and possibly Jurassic.

From this accumulated information on other parts of the Atlantic Coastal Plain the unconsolidated sediment is identified as Upper Cretaceous, Tertiary, and Quaternary; and the semiconsolidated is identified as Cretaceous, primarily Lower Cretaceous, and possibly Jurassic. The significance of the second seismic horizon in the unconsolidated sediment over the continental rise is not known.

From its stratigraphic position, its rather limited extent, and its thickness the consolidated sediment is identified as Triassic. The interpretation is that this is another Triassic basin similar to those found along the East Coast from North Carolina to Acadia.

The only geologic information on the stratigraphy of the outer part of the continental shelf and the contental slope in this area comes from samples taken along the sides of the Georges Bank canyons. Stetson (1936; 1949) describes sandstones of Matawan and Navarro age obtained from rock-dredge tows along the sides of Oceanographer and Gilbert canyons on the edge of the continental shelf. At these locations the canyons have incised 1500–3000 feet (.46–.91 km) below the normal bottom level of 500 feet (.15 km) (Veatch and Smith, 1939, chart 4); this is sufficient to reach down to the semiconsolidated layer. He also describes dredge and core samples of Tertiary age, all of which were obtained in the canyons, and places the contact between the Upper Cretaceous and Tertiary at about 1500 feet (.46 km) below the bottom. This locates it in the unconsolidated sediment and supports the age span given above for this seismic layer. Northrop and Heezen (1951) present a photograph of an Eocene outcrop in a smaller canyon south of Cape Cod and a description of a core taken at the same time.

Crustal Layering

On the continental shelf a single high-velocity basement was measured. This basement is at the surface over central and southern Nova Scotia. It is the Meguma series, metamorphic rocks intruded by granite and gabbro of Devonian age as shown on the recent map by the Geological Survey of Canada (1949). The Meguma consists of the Halifax formation of slate and argillite and the older Goldenville formation of quartzite and slate. It is generally considered Pre-Cambrian but may be in part early Paleozoic. Their thickness has been estimated to be 30,000–35,000 feet (9–10.5 km) (Woodman, 1908, p. 109; Faribault, 1913). The results of profile 56 indicate no seismic discontinuity down to a depth of at least 45,000 feet (14 km).

The seismic velocities measured for the basement on the continental shelf are typical of those found for granites and metamorphics; and the variations in velocity, including that of profile 47, are those that might be expected in passing from granites to metamorphics or through varying degrees of metamorphism.

On the continental rise a second crustal layer was measured in the basement at an

average depth of 30,000 feet (9 km) (Figs. 1–3). Its velocity of 21,640–23,690 ft/sec (6.60–7.22 km/sec) and its position below the basement identify it as the intermediate layer of continental and oceanic seismology. On the longest profile, No. 70, a third crustal layer was measured in the basement at a depth of 52,000 feet (16 km). Its unreversed velocity of 27,810 ft/sec (8.48 km/sec) identifies it as P_n of seismology and the boundary as the Mohorovičić discontinuity.

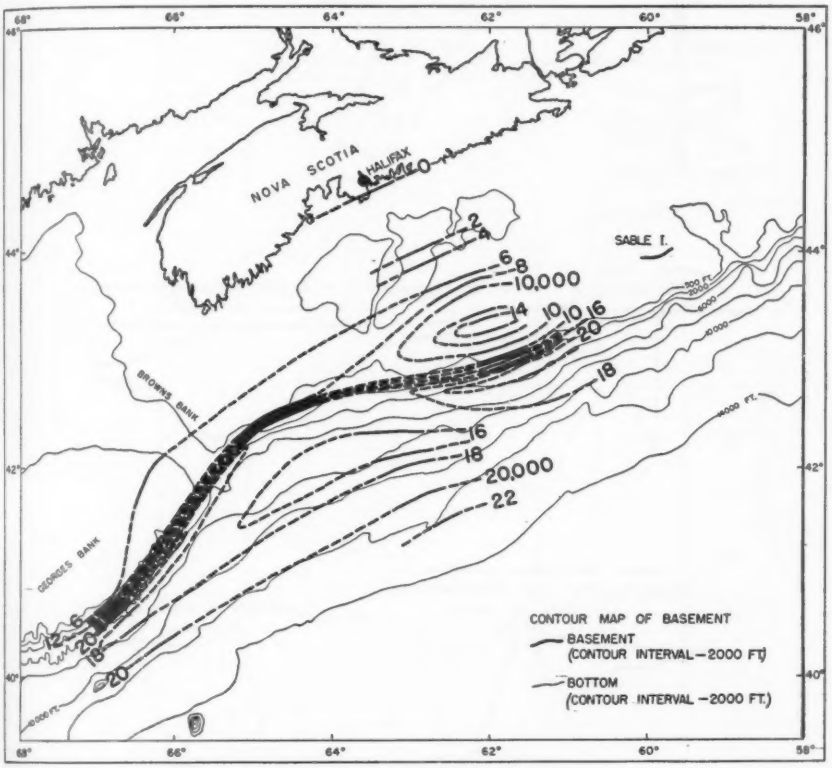


FIGURE 7.—CONTOUR MAP OF BASEMENT

STRUCTURE AND STRATIGRAPHY

I. One of the most prominent features of the crystalline rock basement structure is the abrupt drop in level from 5000–9000 feet (1.5–2.7 km) down to 20,000 feet (6.0 km) under the continental slope (Figs. 2, 3, 4, 7). Sections A and B did not have profiles so located as to measure this abrupt drop directly, but it is delimited by profiles 52 and 54 on section A and by profiles 63 and 57 on section B. Profile 68 of section C did measure it directly. It has a slope of 22° from 5000 feet to 20,000 feet (1.5 to 6.0 km). On each section it is followed by a more gentle upslope of the basement, and on two of the sections this latter feature is followed by a gentle downslope.

It is difficult to say whether this drop represents a large flexure, a fault or series of faults, or perhaps some other feature. No hypotheses are advanced here for its origin or its importance in regional tectonics. The purpose is to point out its presence and dimensions on these three sections across the continental margins.

II. The crystalline basement is very thick under Nova Scotia and the bordering con-

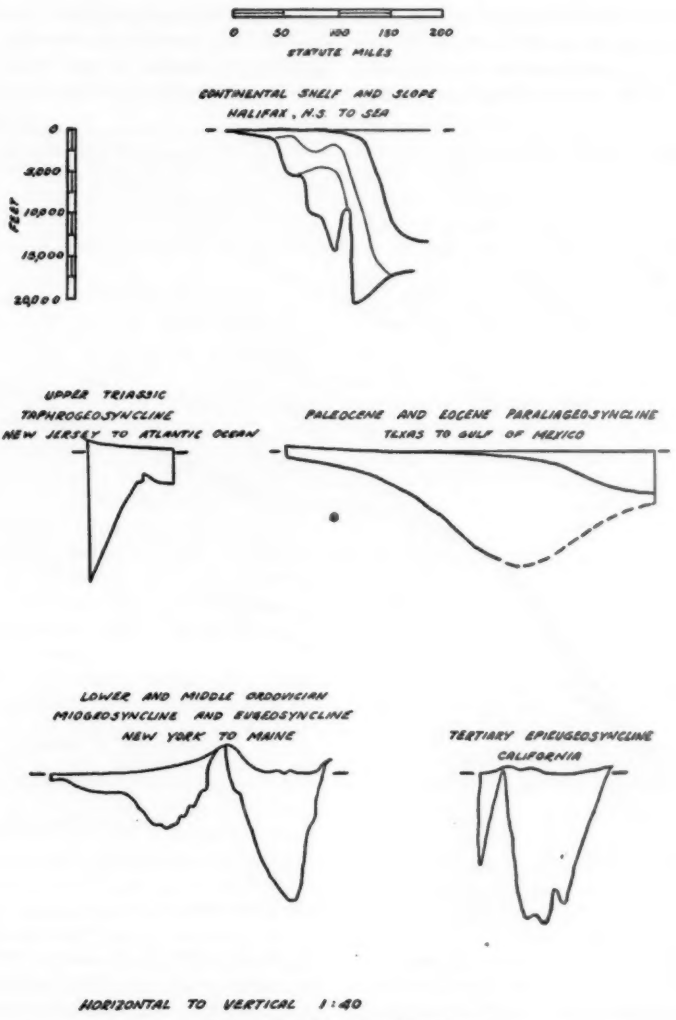


FIGURE 8.—GEOLOGIC SECTIONS

A comparison of the geologic section under the continental shelf, slope, and rise south of Nova Scotia with known geosynclinal sections from Kay (1951).

tinental shelf area. Woodman (1908) and Faribault (1913) estimate 30,000–35,000 feet (9–10.5 km). Profile 56 shows no discontinuity down to 45,000 feet (14 km). However, on the continental rise a lower crustal layer, the intermediate layer of seismology, is measured at an average depth of 30,000 feet (9 km), giving the basement a thickness of 10,000 feet (3 km). The results of others[1] show that the crystalline basement continues to thin and

[1] This is quoted from as yet unpublished results of four separate refraction investigations, one by P. C. Wuenschel south of Nova Scotia, a second by J. Ewing also south of Nova Scotia, a third by J. L. Worzel south of Georges Bank, and a fourth by G. H. Sutton south of Cape Cod.

finally pinches out farther seaward on the continental rise. Under the ocean basins this upper basement is not present (Ewing *et al.*, 1954; Hersey *et al.*, 1952; Officer *et al.*, 1952).

farther from the main orogenic belt. (2) The lower basement velocities on the continental rise represent measurement of the sediments were being deposited seaward during the early

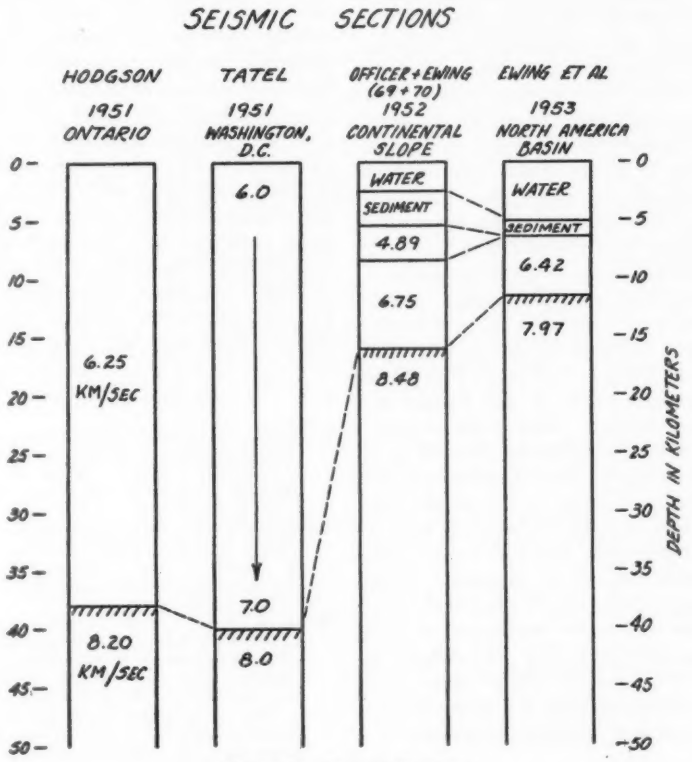


FIGURE 9.—SEISMIC SECTIONS

A comparison of crustal sections from Eastern North America across the continental margins to the North America Basin.

The basement velocities on the continental rise are in general lower than those on the continental shelf (Table 1; Figs. 2, 3, 4). The basement velocities on the continental shelf are typical of highly crystalline rocks, metamorphic rocks or granites. The basement velocities on the continental rise are down in the region of lithified sediments. Two processes are suggested as possible explanations of this phenomenon, both of which may be important. (1) The observed decrease in basement velocity represents decreasing metamorphism of the thinner basement under the continental rise

Paleozoic when great thicknesses of sediment were being deposited landward in the Appalachian geosyncline from sources on the outer part of the continental shelf.

III. In agreement with the results of Ewing *et al.* (1950), we find that the basement does not slope simply and constantly seaward on the continental shelf. In the section from Halifax seaward, there is a great thickness of consolidated sediment of probable Triassic age in one depression and a lesser thickness of semiconsolidated sediment of probable Lower Cretaceous age in another (Fig. 2). Judging from the

stratigraphic distribution of the sedimentary layers, the Triassic was deposited in a basin on the continental shelf when the basement level was higher; the Coastal Plain sediments were deposited on a platform which gradually foundered during the Cretaceous. Prior to the deposition of the unconsolidated sediment (Magothy) the area was uplifted and eroded. The same coincidence between the basement surface shoreward and the top of the semiconsolidated sediment is present on the Halifax section (Fig. 2) as was observed on the New York section (Ewing *et al.*, 1950, Fig. 1).

IV. There is a thick accumulation of Coastal Plain deposits on the continental rise. The semiconsolidated sediment reaches a maximum thickness of 14,000 feet (4.3 km) near the base of the continental slope (Fig. 6); and the unconsolidated sediment reaches a maximum thickness of 10,000 feet (3.0 km) farther out on the continental rise (Fig. 4). The younger unconsolidated sediment overlaps the semiconsolidated sediment, indicating that the area has been building out from the beginning of the Coastal Plain deposition to the present. On the continental slope the sediments, in general, are thin particularly where the continental slope is steep (Fig. 4). A comparison of the sedimentary section from Halifax to the continental rise with known continental sections taken from Kay (1951, Fig. 19) is shown in Figure 8; it is included only to demonstrate that this section is as thick and as extensive as some of the larger known sedimentary sequences.

V. The refraction data does not give a clear-cut answer as to whether the outer banks on the continental shelf—*viz*, Georges Bank, Browns Bank, and Sable Island Bank—are terminal moraines from the last glacial period or cuestas of the Coastal Plain sediment. If the banks were the expression of a terminal moraine, one would expect to pick up an additional refraction layer on the banks which would not be present shoreward off the banks. No such layer was measured along the line of profiles out of Halifax. However, there may be insufficient difference in the physical properties of the moraine and the underlying sediment to identify it as a separate refraction layer.

Seismology

These profiles indicate the change in crustal structure from continent to ocean (Fig. 9). The upper crustal layer of continental seismology, which under Nova Scotia is the thick series of metamorphic rocks and granites, thins on the continental rise and is not present under the deep ocean basins. The intermediate layer rises from a depth of 50,000–80,000 feet (15–25 km) under the continents, to a depth of 30,000 feet (10 km) under the continental rise, and a depth of 20,000 feet (6.5 km) under the ocean basins. The Mohorovičić discontinuity is measured on one profile on the continental rise at a depth of 52,000 feet (16 km) as compared with a depth of 130,000 feet (40 km) under Eastern North America and a depth of 30,000 feet (10 km) below sea level under the ocean basins.

References Cited

Ewing, M., Crary, A. P., and Rutherford, H. M., 1937, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part I, Methods and results: Geol. Soc. Am. Bull., v. 48, p. 753–802.

Ewing, M., Sutton, G. H., and Officer, C. B., 1954, Seismic refraction measurements in the Atlantic Ocean, Part VI, Typical deep stations, North America Basin: Seismol. Soc. Am. Bull., v. 44, p. 21–38.

Ewing, M., Wollard, G. P., and Vine, A. C., 1939, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part III, Barnegat Bay, New Jersey, section: Geol. Soc. Am. Bull., v. 50, p. 257–296.

—— 1940, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part IV, Cape May, New Jersey, section: Geol. Soc. Am. Bull., v. 51, p. 1821–1840.

Ewing, M., Worzel, J. L., Steenland, N. C., and Press, F. (1950) Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part V, Woods Hole, New York, and Cape May sections: Geol. Soc. Am. Bull., v. 61, p. 877–892.

Faribault, E. R., 1913, Excursion in eastern Quebec and the Maritime Provinces: 12th Internat. Geol. Cong. Guidebook 1, p. 158–192.

Geological Survey of Canada, 1949, Geological map of the Maritime Provinces: Map 910A.

Hersey, J. B., Officer, C. B., Johnson, H. R., and Bergstrom, S., 1952, Seismic refraction observations north of the Brownson Deep: Seismol. Soc. Am. Bull., v. 42, p. 291–306.

Hill, M. N., 1952, Seismic refraction shooting in an area of the Eastern Atlantic: Roy. Soc. London Philos. Trans., ser. A, v. 244, p. 561–596.

Kay, M., 1951, North American geosynclines: Geol. Soc. Am. Mem. 48, 161 p.

Northrop, J., and Heezen, B. C., 1951, An outcrop of Eocene sediment on the Continental Slope: Jour. Geology, v. 59, p. 396–399.

Officer, C. B., Ewing, M., and Wuenschel, P. C., 1952, Seismic refraction measurements in the Atlantic Ocean, Part IV, Bermuda, Bermuda Rise, and Nares Basin: Geol. Soc. Am. Bull., v. 63, p. 777–808.

Oliver, J. E., and Drake, C. L., 1951, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part VI, The Long Island area: Geol. Soc. Am. Bull., v. 62, p. 1287–1296.

Skeels, D. C., 1950, Geophysical data on the North Carolina Coastal Plain: Geophysics, v. 15, p. 409–426.

Spangler, W. B., 1950, Subsurface geology of Atlantic Coastal Plain of North Carolina: Am. Assoc. Petroleum Geologists Bull., v. 34, p. 100–132.

Stetson, H. C., 1936, Geology and paleontology of the Georges Bank Canyons, Part I, Geology: Geol. Soc. Am. Bull., v. 47, p. 339–366.

—— 1949, The sediments and stratigraphy of the East Coast continental margin; Georges Bank to Norfolk Canyon: Paper in Physical Oceanography and Meteorology, Mass. Inst. Technology and Woods Hole Oceanogr. Inst., v. 11, no. 2.

Swain, F. M., 1947, Two recent wells in Coastal Plain of North Carolina: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 2054–2060.

Tolstoy, I., Edwards, R. S., and Ewing, M., 1953, Seismic refraction measurements in the Atlantic Ocean, Part III: Seismol. Soc. America Bull., v. 43, p. 35–48.

Veatch, A. C., and Smith, Paul A., 1939, Atlantic submarine valleys of the United States and the Congo submarine valley: Geol. Soc. Am. Special paper 7, 101 p.

Woodman, J. E., 1908, Probable age of the Meguma (gold-bearing series) of Nova Scotia, Geol. Soc. Am. Bull., v. 19, p. 99–112.

Woods Hole Oceanographic Institution, Woods Hole, Mass.; Lamont Geological Observatory (Columbia University), Palisades, N. Y.

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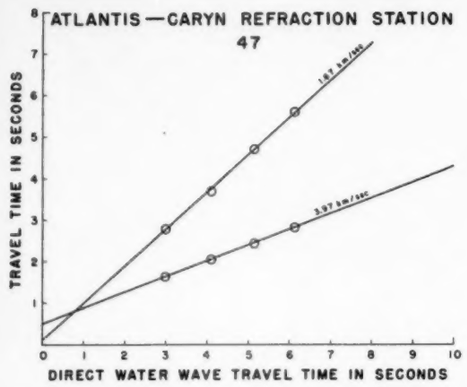
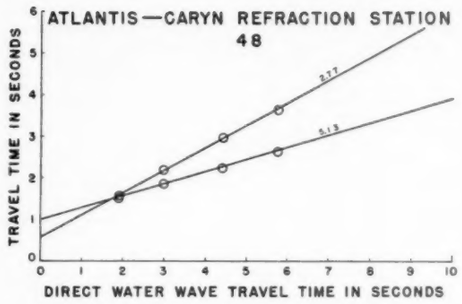
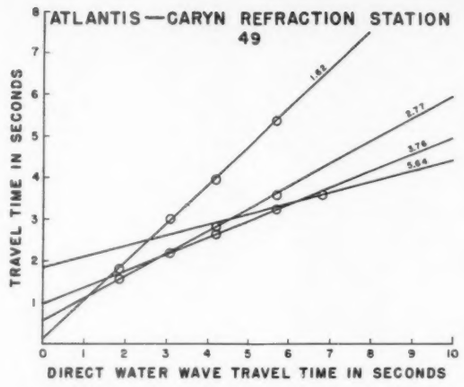
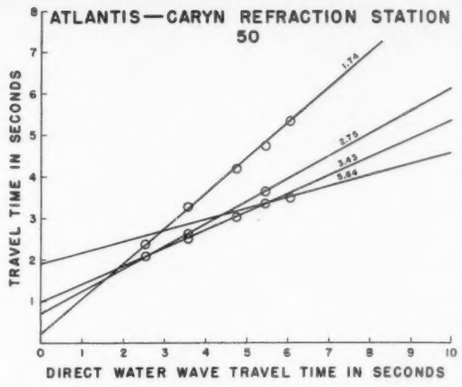
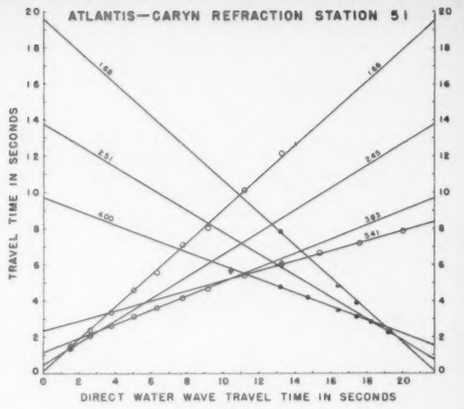
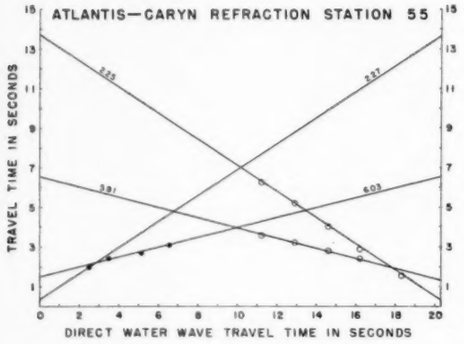


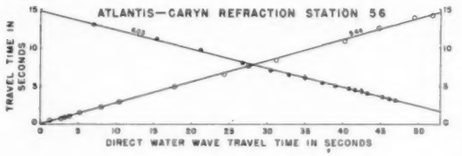


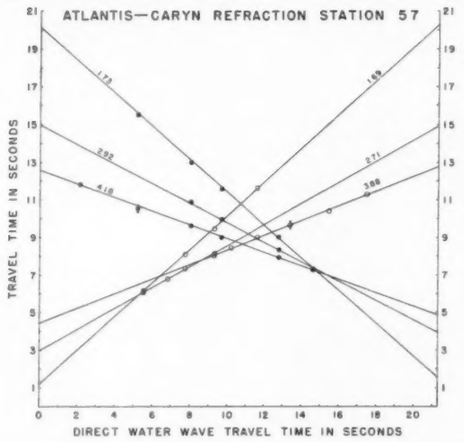


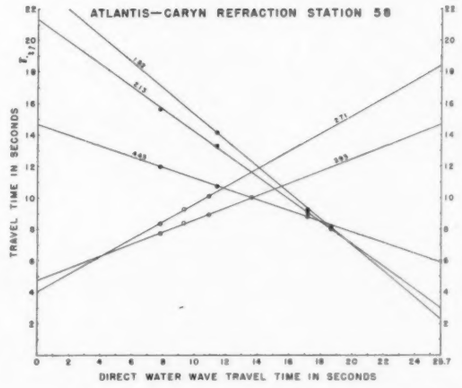


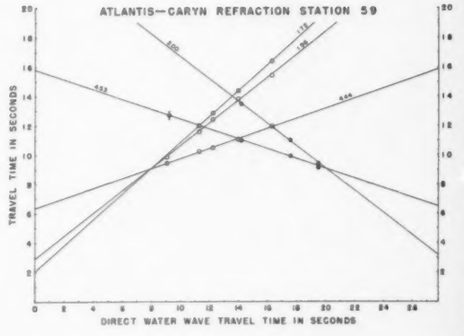


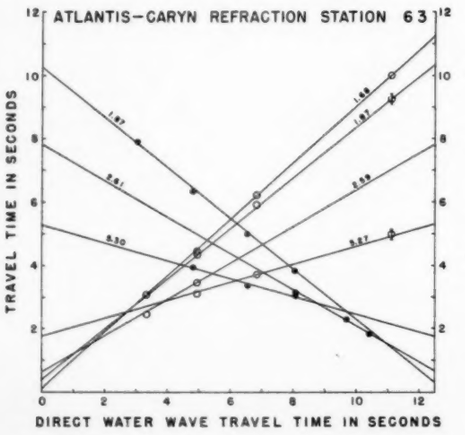


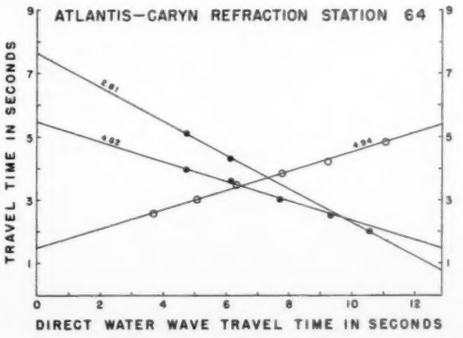


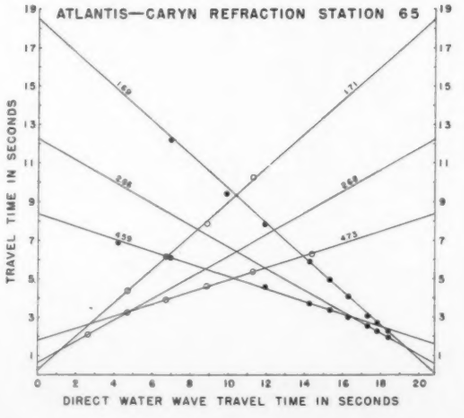


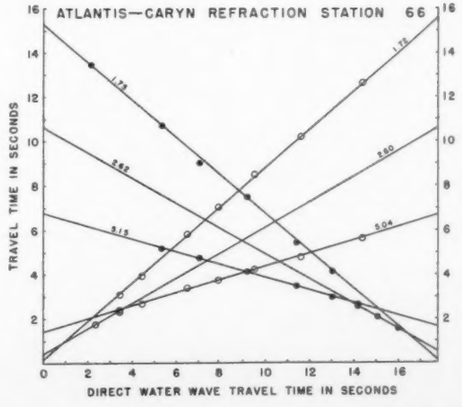


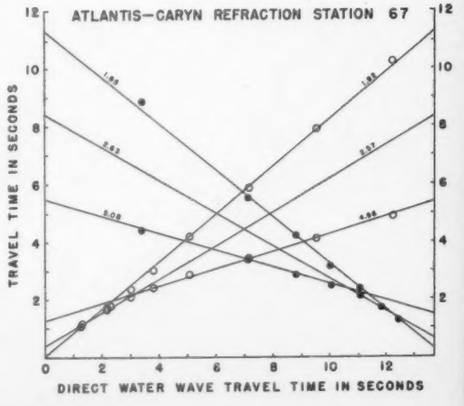




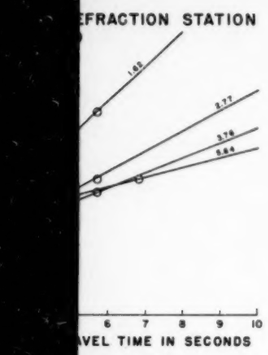


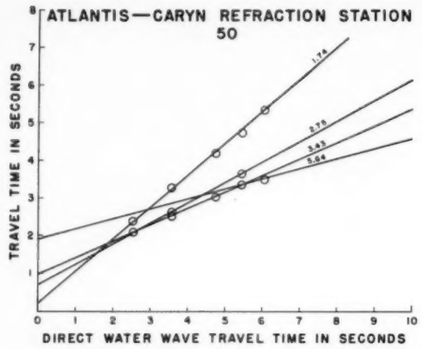


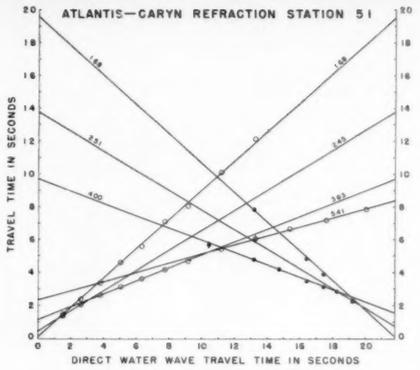


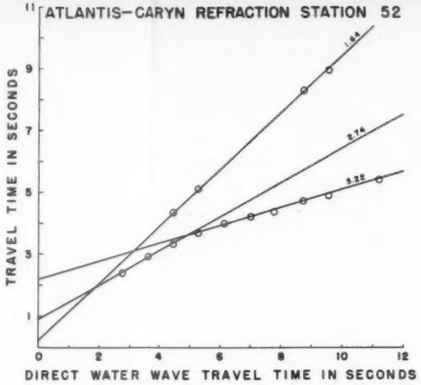


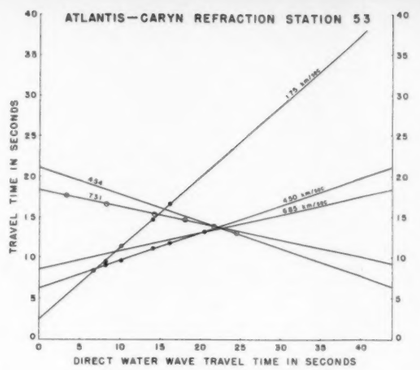
TRAVEL-TIME GRAPHS

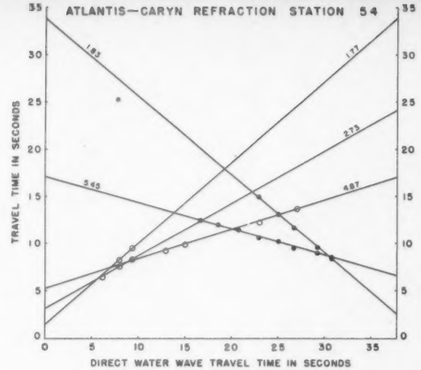


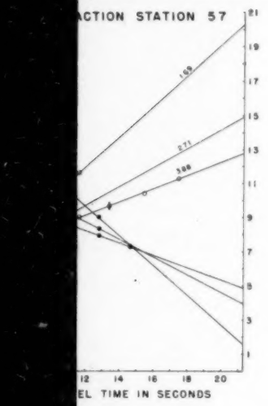


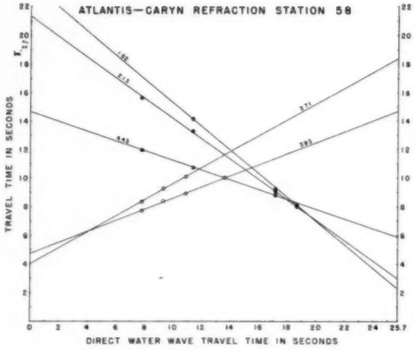


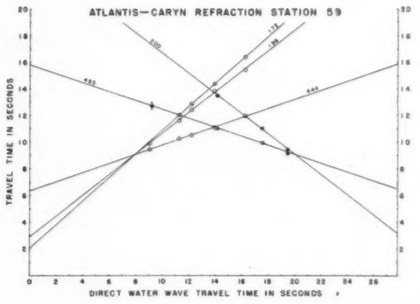


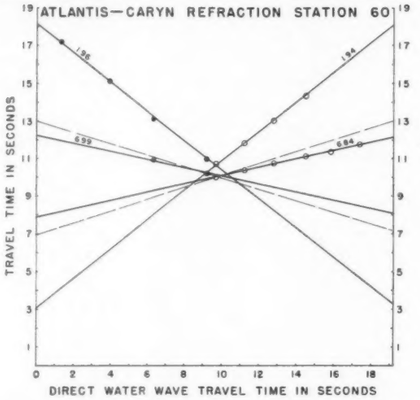


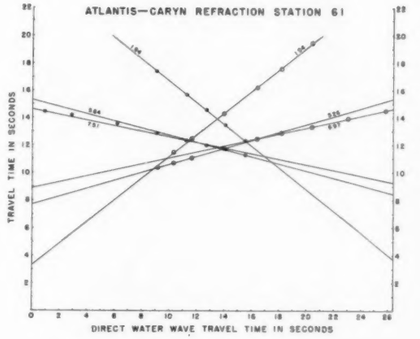


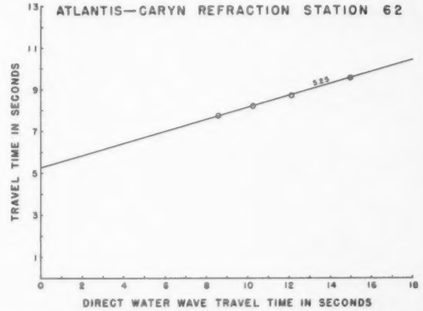


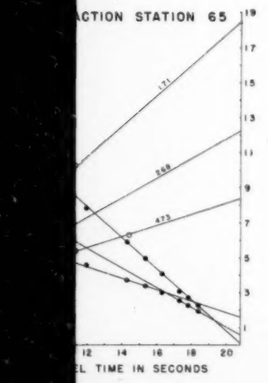


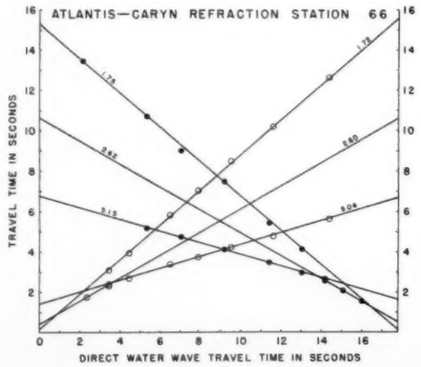


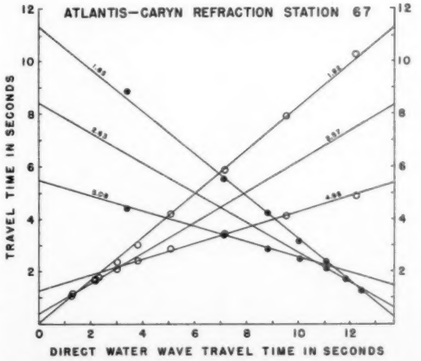


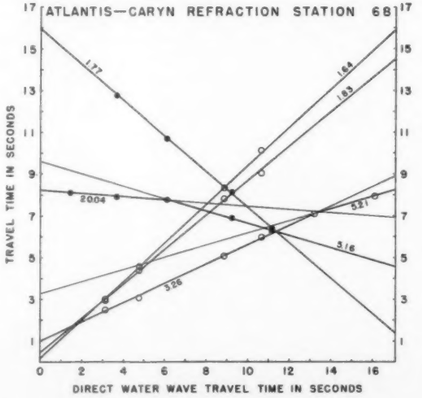


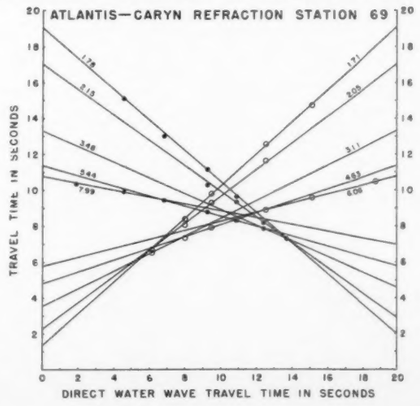


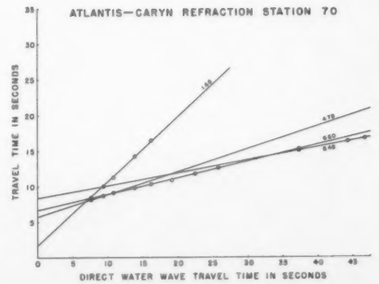












TRAVEL-TIME GRAPHS

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TRAVERTINES AND CAVE DEPOSITS OF THE KAAP ESCARPMENT OF SOUTH AFRICA, AND THE TYPE LOCALITY OF *AUSTRALOPITHECUS AFRICANUS* DART

BY FRANK E. PEABODY

ABSTRACT

The surface travertines, included cave deposits, and other associated phenomena along the Kaap escarpment (Campbell Rand) of the Union of South Africa are mapped and described with emphasis on chronology. The Thabaseek, Norlim, Oxland, and Blue Pool travertines (new names) at Buxton in the Taungs Native Reserve, type locality of *Australopithecus africanus* Dart, are of different ages and are related to each other and to water-cut channels in such a manner as to represent a long, seven-stage sequence of events, the first of which antedates Middle Pleistocene time. Several cave faunas, including the *Australopithecus* fauna, and archeological material of Middle and Late Stone Age of South Africa are correlated with the travertine sequence. *Australopithecus* occurs in the youngest part of the oldest travertine. Other travertines and associated phenomena along the Kaap escarpment are correlated with the Buxton sequence, and a tentative correlation is made with the diamond gravels of the Vaal River. Buxton travertines seem to have been formed during the waning of wet (pluvial) periods; on this basis, two earlier major travertines and two later minor travertines at Buxton correlate with the two earlier major and the two later minor pluvials interpreted from the gravels and terraces of the Vaal River by H. B. S. Cooke. *Australopithecus* and its associated fauna are considered no older than Lower Pleistocene on the basis of physical and biological data. There is no concrete evidence for a Pliocene age.

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Introduction

General Statement

The caves of South Africa which are the most important in the history of early man and australopithecine primates are of two general types: those developed as solution cavities in bedrock dolomite, and those developed as solution cavities in travertine deposited on the dolomite. The Sterkfontein and Makapan caves of the northern Transvaal Province fall into the first category; most of the caves along the Kaap escarpment of northern Cape Province fall into the second.

The Kaap escarpment, popularly known as the Campbell Rand, is the eastern rim of an extensive plateau occupying the northern part of Cape Province near the western borders of the adjoining Orange Free State and Transvaal Provinces. The escarpment is outlined mainly by a cliff-forming dolomite in the dolomitic Campbell Rand series of probable Precambrian age, and may be readily traced for 150 miles from near Vryburg southwestward to Douglas. (Fig. 1). Details of this low but persistent escarpment are described by R. B. Young (1925, p. 59).

Along the escarpment a few large and many small masses of travertine have been deposited, usually near or on the banks of the channels of intermittent streams draining the eastern plateau. The structure of the plateau favors the formation of springs above the cliff-forming dolomite, and the springs are closely associated with the pattern of surface drainage. Some of the springs are perennial, as at Buxton, but most are intermittent. The springs are primarily responsible for the formation of the travertines. Although cliff-forming and sheet (*vlei*) travertines have been and are being formed, the important caves and cave deposits occur in the former.

The travertines constitute a natural resource of economic value for South Africa. Quarry operations begun before 1920 are being increased by employing modern methods. In this way the travertine at Gaap is being rapidly consumed by large scale mining operated by a small modern community of Europeans. Mining operations have opened up countless caves and cave deposits in the travertines, but these are rapidly destroyed and the fossiliferous but lime-poor cave deposits are cast onto the great dumps. The successive rapidly changing cross sections revealed in the quarries represent important chapters in the Quaternary of South Africa. But successive travertine sections, like the ground sections of a fossil, are each destroyed, and a mined-out travertine such as at the old Iscor quarry north of Buxton indicates little of its past history. The writer's latest information (1954) is that Buxton, too, is mined out; presumably many of the features described in this report have been destroyed.

In 1947 and 1948 the paleontological part of the University of California South African Expedition investigated every major travertine and the many small ones between Gaap and Vryburg. The most interesting and significant record of Quaternary events is represented in the travertines of Buxton, and the present paper deals mostly with this locality. Buxton is a small mining community situated below the escarpment and on the west border of the Harts River Valley across from Taungs village (Fig. 1). Since the lime quarry at Buxton is the type locality of the now famous man-ape, *Australopithecus africanus*, an extended description of the geological occurrence is worth while.

The principal results are embodied in the geologic map (Fig. 2) and diagrammatic panorama (Pl. 5) of the Buxton travertines. By using data from an excellent contour map, an aerial photograph, and from drill logs provided by the Northern Lime Company, the writer has reconstructed the contours of the original or prequarry surface with the dumps removed. The position of quarry walls as of 1948 is indicated. At this date the Thabaseek travertine was mined out, except for several little hills

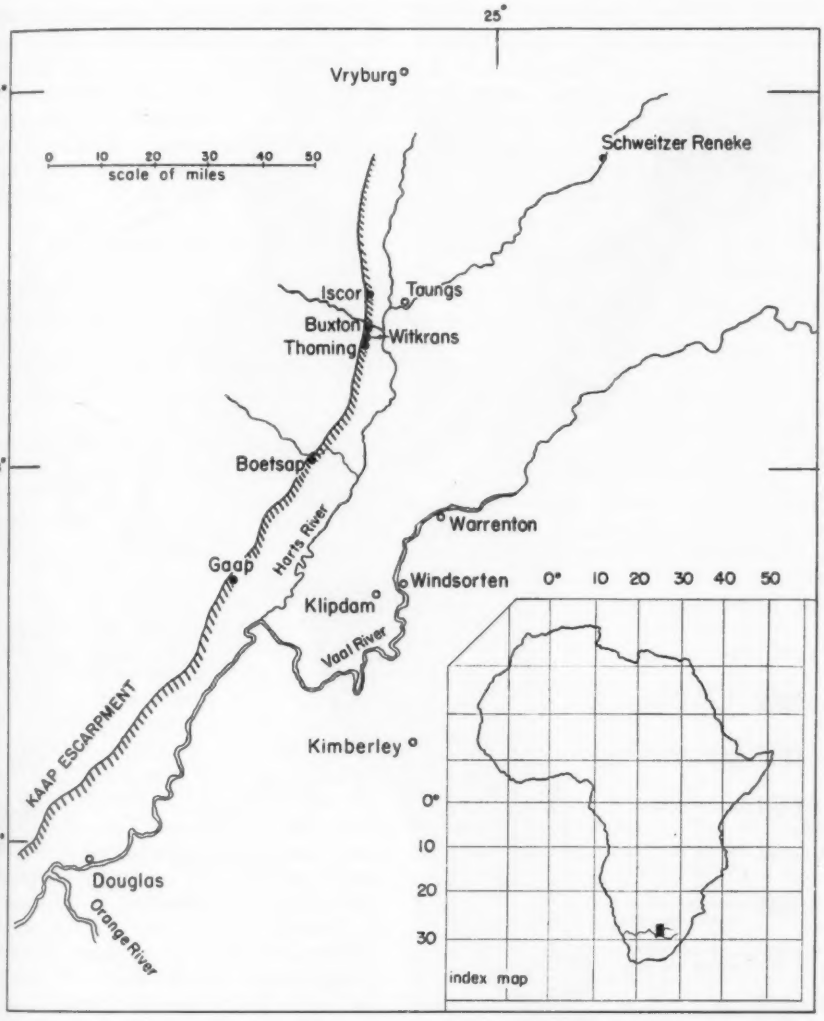

FIGURE 1.—FOSSILIFEROUS AND IMPLEMENTIFEROUS LOCALITIES ALONG KAAP ESCARPMENT
Investigated by University of California African Expedition

that preserved portions of the original surface; the Norlim travertine was two-thirds exhausted, and quarrying had begun in the upstream and downstream sides of the Oxland travertine; the Blue Pool travertine was to be mined in the near future. For reconstruction of the pre-quarry surface in the oldest and most critical areas in the southern quarry some reliance had to be placed upon old photographs and upon eye-witness reports from veteran employees of the Northern Lime Company.

Recovery of fossils from consolidated deposits at Buxton was greatly facilitated by the extensive use of pneumatic drills and dynamite. A successful practice was to blast away the walls of a cave, being careful to avoid blasting directly into the cave deposit, and to place minimum charges under the deposit and

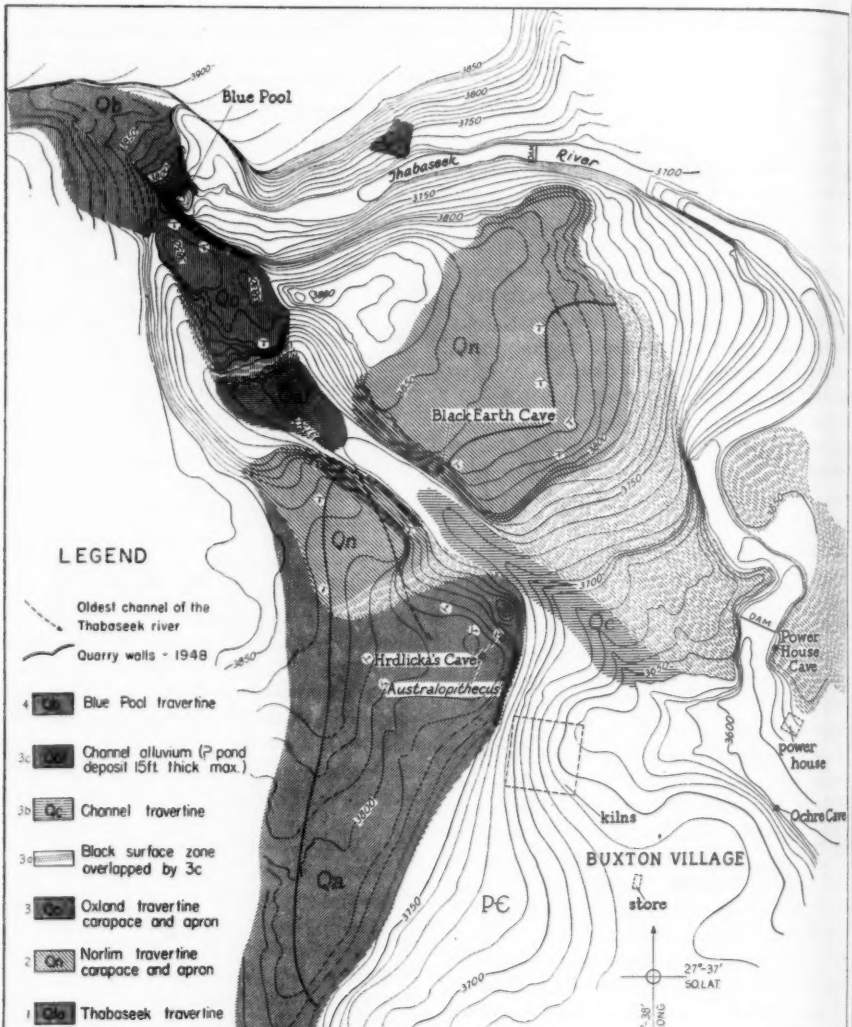

FIGURE 2.—GEOLOGIC MAP (PREQUARRY SURFACE RECONSTRUCTED) OF TRAVERTINES AT BUXTON, TAUNGS NATIVE RESERVE, CAPE PROVINCE, UNION OF SOUTH AFRICA

crack it into transverse sections which could be easily removed and examined. This method avoided loss of fossils due to pulverization in place and scattering of fragments. Unconsolidated deposits were excavated using intervals of 6 inches and with close attention to mapping the different horizons. Also, the writer took representative samples of consolidated and unconsolidated deposits, whether fossiliferous or not, for future petrographic

study. Archeological materials collected were given to the Archeological Survey of South Africa for study. All this material, except for certain specimens, described by Dr. Malan in a description (in manuscript) of the Wilton culture of Little Witkrans, is now at the Department of Anthropology, University of California.

Acknowledgment

Camp (1948, p. 552) made broad acknowledgements for the entire South African Expedition, Southern Section, of the University of California. The work of the paleontological party along the Kaap escarpment was facilitated by officials of the Northern Lime Company, Ltd. The gracious hospitality and enthusiastic co-operation of Mr. and Mrs. Richard Oxland of Buxton are gratefully acknowledged. As Works Manager for the Northern Lime Company, Mr. Oxland made available to the expedition housing, men, materials, and quarry records, thereby contributing immensely to the investigation. Mr. Oxland, a mining engineer, also rendered valuable assistance by collecting and synthesizing eye-witness reports on prequarry surfaces. Other company personnel, especially Mr. Duplessis, quarry manager, and Messrs. Erasmus, Roberts, and Freer gave generous help in drilling and blasting operations. Mr. Simon Zagt, field geologist of the South African Geological Survey, assisted with certain excavations and was especially helpful in establishing contour levels north of the Thabaseek River (an area not covered by previous maps). Mr. James Kitching of the Bernard Price Institute for Paleontological Research helped with some of the excavating. Master "Saakie" Hayward, Buxton schoolboy, rendered valuable service in the collection of fossils and artifacts and was instrumental in the discovery of the Middle Stone Age cave deposit at Witkrans. Many other local citizens contributed to the well-being of the party during the investigation.

Professor Raymond Dart of the University of the Witwatersrand, Dr. Sidney Haughton, at that time Director of the Geological Survey of South Africa, Dr. Vivian Fitzsimons, Director of the Transvaal Museum, and Drs. Robert Broom and John Robinson gave advice and encouragement in the course of our investigation. Drs. C. van Riet Lowe and Berry Malan of the Archaeological Survey of South Africa collaborated in the study of implementiferous sites along the Kaap escarpment, and expedited shipment of fossils.

Persons in the United States who gave assistance are: Mr. Victor Hogg and Mr. Owen J. Poe, who helped prepare illustrations; Dr. Donald Savage, who assisted with the preliminary faunal list; Miss Ada Swineford and Mr. Russel Runnels of the Kansas State Geological Survey, who assayed certain rock samples; Miss Madeline Peabody, who provided a photostat copy of African field notes; Professors Robert W. Wilson and Charles L. Camp, who read the manuscript critically.

Professor Camp directed the investigation and with the writer conducted the paleontological and archeological work along the Kaap escarpment. He does not necessarily share the opinions and conclusions expressed in this report.

History of Buxton Travertines, Taungs Native Reserve

Preliminary Remarks

In a study of the travertines of the Kaap escarpment from Boetsap to Buxton Young (1925, p. 64) concludes that an increase of aridity favored the growth of the travertines. He notes that the African travertines resemble South American travertines described by Branner (1911) from the Bahia region of Brazil. Branner (p. 193) describes travertine barriers encroaching upon and in some cases blocking river channels, and concludes that these natural dams form during periods of low rainfall.

Young is the first to observe that the Buxton travertines have been involved in a sequence of events beginning with deposition of travertine and ending with a major diversion of the associated river channel. However, Young (1925, p. 66) concludes that the Buxton travertines were deposited continuously, whereas present evidence (from many new sections developed by quarrying operations

since 1925) indicates at least four depositions of travertine related to a long Quaternary history of stream blocking, stream shunting, and stream cutting. The caves and cave deposits may be correlated with this history. Young attributes the diversion of the Thabaseek River to domestic stream piracy alone, but damming by the Oxland travertine was probably the primary factor in this diversion.

At several localities along the Kaap escarpment, especially at the old Iscor quarry north of Buxton, there is definite evidence that a cliff-forming travertine building out from the side of a channel causes a pronounced lateral shunting of the channel. When the bedrock is shaly, the effect is more pronounced. At Iscor, the otherwise straight channel loops northward around the position of the travertine. Young (1925, p. 59) notes that at Thoming the stream channel is "drawn toward the two extremities," that is, diverted north and south around the margins of the travertine. The Blue Pool travertine (Fig. 2) is at present shunting the Thabaseek River northward and is causing a broad excavation in the cliff of bedrock forming the north wall of the channel. If the travertine builds out fast enough, a dam may be formed before any appreciable erosion can sculpture the opposite side of the channel. The only record of this occurrence is at Buxton where the Oxland travertine blocked, then diverted, the channel, and the Norlim travertine blocked the channel but was bisected subsequently by stream erosion. It should be noted that in this example an older travertine rather than bedrock formed the opposite wall.

The genesis of cliff-forming travertines along the Kaap escarpment is more complex than appears on superficial examination. Several of the biscuitlike masses built out from the escarpment show a distinctly duplex structure. For example, at Thoming a deep trench reveals that a mass of roughly hemispherical, overlapping sheets of lime, curving steeply away from the source, partly overrides an apron of parallel-bedded, sandy, rubbly limestone which dips gently away from the escarpment. In a vertical plane section parallel to the escarpment, the contact between the overriding carapace lime and the overridden apron lime appears as a distinct horizontal line. The apron is impure lime in contrast with the nearly pure lime of the carapace; consequently the apron is not quarried except as access is needed to the overlying carapace lime. The duplex structure noted at Thoming is equally well exhibited in excavations in the Oxland travertine at Buxton (Fig. 7). Here the apron lime shows evidence of deposition by running water. Stringers of well-rounded pebbles occur in the poorly sorted rubble. It is not possible to state in these cases whether the apron and carapace were built up simultaneously or whether the apron predates the carapace formation. In any event, the combination represents closely related phenomena, possibly reflecting a trend from wetter to drier conditions as the source waters diminish.

Caves and cave deposits in the travertines nearly always occur in the carapace lime. Caves develop best along the contact between layers of the carapace; and, since the layers tend to be hemispherical, the cave may be arc-shaped in floor plan, as is Witkrans cave (Fig. 8). In large masses of travertine a cave system tends to parallel the strike of the steeply dipping layers of carapace lime, as shown by the *Australopithecus* and Black Earth Caves (Figs. 4, 5).

Synopsis of Physical History

Accumulated data, mentioned earlier and embodied in the map and panorama, make possible a synopsis of the physical history of the Buxton travertines. Some of the important cave deposits may be related to the stages of travertine formation.

STAGE 1: The oldest channel of the Thabaseek River, as detected and outlined by extensive core drilling, flowed in a more southerly direction and more obliquely to the escarpment than did later channels (Fig. 2). Remnants of the eastern and western sides of the channel are exposed in the present quarry floor (1948); maximum depth of the channel is at 3680 feet elevation. However, the channel does not continue, as expected, to a point near the kilns; instead, there is a bedrock high at this point. Possibly the channel went underground and issued forth at the foot of the escarpment. If a channel was incised in the shale below the escarpment, erosion has modified it. The broad depression leading up to

the cliff in the Thabaseek travertine may be the remnant.

The oldest channel cuts the escarpment obliquely (S.25°E.) relative to later channels, and the writer suspects that a joint plane or perhaps a minor fault controlled the direction. South of Buxton and between Witkrans and Thoming, a sharply incised canyon cuts obliquely through the escarpment similarly and is developed along an eroded joint plane.

Deposition of lime in the oldest channel of the Thabaseek River began with cementing of a thick surface rubble of dolomite and shale from pebble to boulder size (Fig. 6 B). The result is a coarse, compact breccia which probably represents the oldest secondary lime deposit at Buxton. No fragments of pre-existing breccias occur in this oldest breccia. Following the consolidation of surface rubble, the channel was blocked permanently by the first stages in the building of the [1] Thabaseek travertine. Then, at some later time, but prior to Stage 4, at least two large caves developed near bedrock more or less coincident with the course of the old channel (Pl. 1, fig. 3). Thus, for a time subterranean drainage seems to have followed the original bedrock channel until stream erosion bisected the Norlim travertine (Stage 4). One of the large caves was filled successively by two accumulations of solidly cemented breccia, each sealed by mammillary lime, followed by cemented, water-laid sand with stringers of pebbles, followed by unconsolidated red sand showing no bedding planes. The breccia in the cave and the older surface breccia are difficult to differentiate; fragmentary bones and teeth of ungulate mammals were found in what was judged to be the older surface breccia (F. E. P. Loc. 38-1). If this is true, the remains are the oldest fossils found at Buxton. No fossils (or artifacts) were definitely located in the cave breccia, although a few bones and teeth occur in later fills in the same cave system (F. E. P. Loc. 38-28).

The Thabaseek travertine, which is presumed to have blocked the original channel for the first time, continued to build out from the escarpment to at least the area shown on the map (Fig. 2). A section exposed on the north side of the hill containing the Hrdlicka site (Pl. 2, fig. 2; Fig. 3) shows a travertine of impure, apron type dipping gently southward and overlain by carapace lime which contains, not far away, the *Australopithecus* Cave. The southward dip of the apron lime is nearly the opposite of dips in the overlying carapace lime, and indicates that travertine equivalent to at least part of the Thabaseek travertine on the south side of the original channel was built out from the north side, too.

A cave system, developed in the eastern periphery and youngest portion of the Thabaseek travertine, accumulated deposits containing many baboons and *Australopithecus*. The cave deposit (Fig. 4) containing the manape is demonstrably the earliest of at least three generations of cavity fillings. The latest contains artifacts of the Middle Stone Age of South Africa.

STAGE 2: Erosion of relatively long duration lowered the surface of the Thabaseek travertine, as attested by outlying knolls, ridges, and truncated fissure deposits. Also, southern portions of the apron and some peripheral carapace lime apparently have been removed. The surface of the next oldest travertine, the Norlim, is not similarly affected, and nowhere in it occur generations of cave fills such as found in the Thabaseek travertine (Fig. 4).

STAGE 3: A later and larger body of travertine, the Norlim travertine (taken from the code name of the Northern Lime Company), was deposited along the escarpment on the north side of the Thabaseek River. This travertine built southward, more effectively blocked the old Thabaseek channel, and partly overlapped the older Thabaseek travertine (Pl. 2, fig. 1). An extensive apron was formed which extended far down the slope of the soft shale below the escarpment. Several subterranean channels developed at the contact of the apron with bedrock and were transected by the later diversion of the Thabaseek (Stage 6). One cave thus formed was used by primitive man (Powerhouse Cave, Pl. 5). The surface of the Norlim travertine shows much less erosion than that of the Thabaseek travertine; and nowhere is there evidence of

[1] Selected as a new name for the travertine in which the *Australopithecus* Cave system was developed. The use of "*Australopithecus*" would be ambiguous in meaning; the use of "Taungs" would be confusing, for it has been applied loosely to cave deposits of Buxton prior to this report.

three generations of cave fillings. Nothing comparable to the *Australopithecus* fauna occurs. For these reasons as well as the overlapping relationship, the Norlim travertine is considered definitely younger, probably much younger than the Thabaseek travertine. Nevertheless, in both travertines numerous fissures are filled with unconsolidated red sand.

The Norlim travertine formed a nearly perfect dam across the Thabaseek, but the little valley extending back into the Thabaseek travertine may have been developed by flow around the western edge of the younger Norlim travertine.

STAGE 4: The Thabaseek River re-established its channel in a direction slightly different from the original course by vigorously cutting through the Norlim travertine and down into bedrock (Fig. 6). A cave system in the Norlim travertine was intersected and later accumulated an important fossil record (Black Earth Cave). The walls of the canyon were nearly vertical and remain so. The dip of the carapace lime on both sides of the canyon indicates that the lime on the south side was originally continuous to the north side and consequently deposited by springs on the north side.

A talus composed of sand and angular boulders of bedrock and of the oldest breccia (Stage 1) accumulated at the foot of the canyon walls and is now cemented fairly solidly. An excellent cross section, developed in the south wall of the canyon by quarry operations (Pl. 2, fig. 1 D; Fig. 6), chronicles a series of events in the history of the canyon. A vigorous erosion cut the canyon and exposed not only bedrock but also the oldest breccia of Stage 1, and probably cleaned out any deposits which had accumulated behind the natural dam of travertine. Then diminution of stream flow allowed the accumulation of a talus of drift sand mixed with rock falls from the canyon walls. Formation of the talus may belong in Stage 5, but it is included here because it must have followed close upon the cessation of canyon cutting by the Thabaseek River. Although the talus was formed on both

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PLATE 1.—BUXTON TRAVERTINES

PHOTOGRAPHS TAKEN IN 1948, EXCEPTING FIGURE 2

FIGURE 1. KILNS AND QUARRY DUMPS OF NORTHERN LIME CO., LTD.
View looking westward.

FIGURE 2. BUXTON QUARRIES IN 1931
Courtesy of Northern Lime Co. View looking northwest. Quarrying had not yet reached mouth (upper right) of canyon cut in Norlim travertine; hill on left, preserving part of prequarry surface, is same as hill shown in Plate 2, figure 2, extreme right, in 1948.

FIGURE 3. DEEP CAVE DEPOSIT EXPOSED 90 FEET BELOW SURFACE OF NORLIM TRAVERTINE
Here Norlim overlaps Thabaseek. Inked line shows otherwise indistinct boundary of cave.

FIGURE 4. TWO SKULLS OF FOSSIL BABOONS
From red, sandy limestone of dry phase of *Australopithecus* Cave.

FIGURE 5. SKULL OF FOSSIL BABOON
Occurring in wet phase of *Australopithecus* Cave. Frontal section of skull indicated by hammer point. Vertical streaks are shellac stains.

PLATE 2.—BUXTON TRAVERTINES

FIGURE 1. PANORAMA OF BUXTON QUARRIES
View looking northwest from Hrdlicka site. Canyon (center) cut through Norlim travertine; upstream from canyon, Oxland travertine (A), with trench leading up to quarry in its downstream face; B—prequarry surface preserved on small hill; C—Black Earth Cave; D—location of section shown in Fig. 6. Hill in immediate foreground is north end of Thabaseek travertine containing the Hrdlicka site.

FIGURE 2. VIEW FROM BUXTON QUARRIES
Looking south, and showing four hills preserving remnants of prequarry surface. Remnant of Thabaseek travertine (point of view of fig. 1, above) indicated by two arrows on left is site of *Australopithecus* Cave.

FIGURE 3. QUARRY IN DOWNSTREAM SIDE OF OXLAND TRAVERTINE
Showing Channel alluvium overlapping Oxland apron; view looking south. Excavated alluvium, dumped along edges of trench, shows on skyline.

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 1

FIGURE 2

BUXTON TRAVERTINES

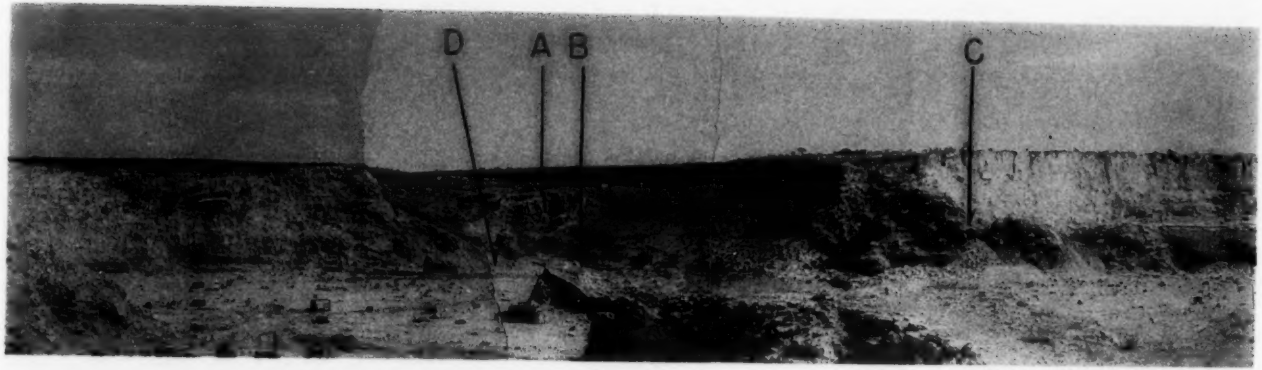

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

BUXTON AND WITKRANS TRAVERTINES

PEABODY, PL. 8

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FIGURE 3

FIGURE 4

FIGURE 1

FIGURE 2

sides of the canyon, it did not extend to the middle of the channel. Possibly the talus accumulated while the Oxland travertine (Stage 5) was forming. In any event, the talus on both sides of the canyon exhibits a superficial zone of black laminations similar to that covering the apron of the Oxland travertine; the very existence of the talus indicates cessation of the vigorous stream erosion which carved the canyon.

The incisive contours of the canyon cut through the Norlim travertine suggest a deep channel below the mouth of the canyon approximately in the position of the Channel travertine (Fig. 2). Four borings in the travertine just west of Powerhouse Cave show that the base of the travertine here is 55, 80, 90, and 100 feet below the present surface. The base of the neighboring Norlim apron is only 35–45 feet below the present surface.

STAGE 5: The channel of the Thabaseek River was blocked once again, this time by the Oxland travertine (named for Mr. Richard Oxland, who directed the first quarry work in this travertine). The Oxland travertine built out from the north wall of the channel 200–300 yards upstream from the Norlim travertine. A sloping apron of rubbly lime developed and extended down the channel cut through the Norlim travertine. At approximately the same time, the channel below the canyon mouth must have been filled by the Channel travertine with a maximum thickness of 100 feet; since its deposition it has been incised with a shallow channel. The surface of the Oxland apron was covered by a black "varnish" which consists of many thin laminae of black, manganiferous lime. This black zone is several inches deep, and the pebbles and cobbles in it are coated, showing in section a series of concentric halos. The black zone is developed also on the cemented talus (Stage 4) at the foot of the canyon walls immediately downstream, and is probably contemporaneous with the zone on the Oxland apron. A similar zone occurs in Witkrans Cave.

Russel Runnels reports (written statement) that samples of the black zone from the Oxland

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PLATE 3.—BUXTON AND WITKRANS TRAVERTINES

FIGURE 1. HRDLICKA SITE IN AUSTRALOPITHECUS CAVE

Showing circular mass of wet phase deposit on man's left. Farther left is exposed black earth in pipe penetrating sterile, red earth and containing Middle Stone Age artifacts.

FIGURE 2. BLACK EARTH CAVE (arrows) IN NORLIM TRAVERTINE

Cliff at skyline is 100 feet above quarry floor in foreground.

FIGURE 3. WITKRANS CAVE

Showing cemented deposit of Middle Stone Age (at head of pick) overlain by unconsolidated deposit of Late Stone Age (middle of pick handle). The figure is "Saakie" Hayward, who discovered deposit.

FIGURE 4. STONE BLADE OF MIDDLE STONE AGE

Cemented in matrix with bone fragments from deposit of Witkrans Cave.

PLATE 4.—TRAVERTINES OF KAAP ESCARPMENT

FIGURE 1. VIEW LOOKING EASTWARD FROM NORTH AREA OF OXLAND TRAVERTINE AND DOWN PRESENT CHANNEL OF THABASEEK RIVER

Showing circular Blue Pool and upper end of artificial reservoir. Oxland travertine (right third of view) abutts isolated hill of bedrock in middle foreground. Boulders of Oxland travertine 25 ft. in diameter on talus slope beyond Blue Pool. Black line across lip of Blue Pool is ledge of bedrock developed along joint plane. Photograph by C. L. Camp.

FIGURE 2. POOLS MADE BY LIME TERRACES

Inhabited by fish, crabs, and limpets in bed of Thabaseek River; approximately one mile upstream from Blue Pool. Pipes in foreground convey spring water to Buxton. Photograph by C. L. Camp.

FIGURE 3. SMALL BUTTES OF PRECAMBRIAN SHALE CAPPED WITH TRAVERTINE

Isolated from main Kaap escarpment near Boetsap. View looking south.

FIGURE 4. VIEW LOOKING NORTHEAST ALONG KAAP ESCARPMENT FROM MIDDLE STONE AGE SHELTER AT LITTLE WITKRANS

Witkrans, with black opening to baboon grotto (left arrow), and smoke from Buxton kilns (right arrow) appear in background. Photograph by Philip Ray.

apron and from Witkrans Cave are similar and consist of a mixture of manganiferous minerals (*e.g.* pyrolusite and psilomelane); a manganiferous surface zone "is observed very often in sedimentary rocks especially in semi-arid areas. For example, there are extensive surface coatings on Niobrara chalk in Western Kansas." In Runnels' opinion, the black zone at Buxton and at Witkrans formed under "conditions at least partially due to seasonal cycles which include a semi-arid season."

The Oxland travertine is demonstrably younger than the Norlim travertine as indicated by topographic relationships; also, the former is surely younger than the canyon cut through the latter. Furthermore, there are few fissures in the Oxland travertine and none filled with the red, sandy earth so prominent in the two older travertines. Lithologically the Oxland travertine and its included deposits resemble the Thoming travertine.

A puzzling feature is a large fissure or cave deposit at the base of the cliff of carapace lime and in the apron lime of the Oxland travertine (Fig. 7 C; F. E. P. Loc. 38-7b). The deposit is broadly exposed at the surface except for a veneer of cemented cobbles and is cemented to a tough, punky mass containing scraps of bone and teeth of *Equus*. The breccia, excellently exposed in section by quarry work, clearly antedates the Channel alluvium of Stage 6 because the cemented cobbles overlying it are overlapped in turn by the alluvium. The breccia may represent a cave deposit or shelter deposit recently uncovered by slight marginal erosion and recession of the carapace lime, and is probably older than the cave deposit described by Tobias (*See* section on Miscellaneous Localities).

STAGE 6: The dam formed by the Oxland travertine, and perhaps aided by domestic stream piracy, diverted the Thabaseek River north of the Norlim travertine where it cut a deep canyon. The river curved around the travertine and followed either a pre-existing channel or a joint system in the dolomite in such a way as to transect the Norlim apron and rejoin the old channel near the present powerhouse. A subterranean channel trending northwest to southeast in the base of the apron was exposed, and a cave, thus formed, subsequently became inhabited by man. (*See* Powerhouse Cave.)

The diverted waters of the Thabaseek River cut sharply into the upstream side of the Oxland travertine. The existing vertical cut overlooking Blue Pool (Pl. 4, fig. 1) plainly shows in the attitude of the hemispherical layers of carapace lime that the Oxland travertine was in a sense beheaded by the diversion it caused, and thus antedates the great diversion of the Thabaseek River.

Channel alluvium, over 15 feet thick in its central area, accumulated below the Oxland travertine and overlapped its apron (Pl. 2, fig. 3). The soil extends downstream and part way into the canyon in the Norlim travertine. The manganiferous surface zone coating the Oxland apron passes unchanged under the soil; clearly the soil is younger than the surface zone. The soil lacks any stratification, is blocky and tough, and is shot through with granules of bog manganese (Dr. John C. Frye, personal communication). Probably the soil accumulated in a swampy area formed by seepage below the dam of Oxland travertine. At the same time the Thabaseek River was diverted northward (Fig. 2). Physical relationships preclude the possibility that the soil is older and represents an accumulation above a dam formed by the Norlim travertine (Stage 3).

During this stage black earth, probably manganiferous, accumulated in depressions and in shallow pipes in both the Norlim and Thabaseek travertines. A pipe at the Hrdlicka site (Pl. 3, fig. 1; Fig. 4 D) accumulated artifacts of advanced technique similar to those of the Witkrans Cave deposit of Middle Stone Age (Fig. 8).

STAGE 7: The last important event at Buxton was the renewed deposition of travertine in the diverted channel of the Thabaseek River. The main area of deposition is on the escarpment just above the plunge pool (Blue Pool). The Blue Pool travertine closely resembles the Oxland travertine but is younger.

Occasional torrents such as occurred early in 1948 (Oxland and Zagt, verbal communication) send a cascade of water over the Blue Pool travertine and into the Blue Pool, but a large volume of water is shunted northward around the main body of the travertine and

against the bedrock. The contours here, and the recession of part of the lime cliff, suggest that the Blue Pool travertine is being eroded faster than it is growing (Fig. 2).

A small body of carapace lime is building out from the southwest border of the Blue Pool; farther downstream, lime terraces in the channel and miniature carapaces on the channel walls are forming. A mile above the Blue Pool there are large terraced pools (Pl. 4, fig. 2) at the main outlet of the perennial spring which feeds the Blue Pool. Fish and crabs are plentiful and attest the perennial nature of the spring.

Fossiliferous and/or Implementiferous Localities

General statement.—The foregoing synopsis lays the physical basis for integrating the fossil- and implement-bearing deposits at Buxton with the travertine sequence. A complete study of fossils and artifacts will add to but probably will not alter the sequence presented. Each locality is described and fitted as well as possible into the travertine sequence. Admittedly, there is little about a cave or its deposits to indicate exact time of origin, and the Quaternary fossils are of little help at present, despite estimates of age based mainly upon the presence or absence of extinct forms (Broom and Schepers, 1946, p. 30). However, there is a definite and complicated sequence of physical events at Buxton, and it is possible at this time to date approximately the important localities relative to the travertine sequence. Also, the geologic occurrence of *Australopithecus africanus* is described in detail.

Australopithecus *Cave.*—When the skull of *Australopithecus* was discovered in a cave deposit at Buxton in 1924, little was noted concerning the relation of the cave deposit to other deposits or to the surrounding travertine. Young (1925, p. 62) does not clearly describe the occurrence and infers that the "sandy limestone" (Bushman klip) and the unconsolidated red sand are contemporaneous. The miners continued their work leaving no trace of the exact site except for a small fissure fill extending below the quarry floor. Fortunately, the lime here became so impure that quarrying was soon discontinued, but not until the quarry floor was extended approximately 100 feet beyond the site where the skull was found. Later quarry operations at a lower level

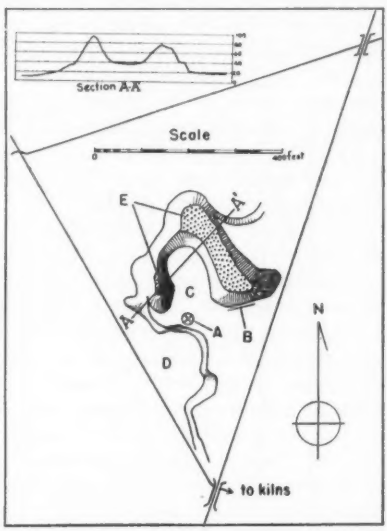

FIGURE 3.—TYPE LOCALITY OF AUSTRALOPITHECUS AFRICANUS DART IN 1948

Shown with reference to triangle of three main haulage tracks of Buxton quarries: A—approximate position, now destroyed, where skull was found; B—Hrdlicka site; C—quarry level of 1924; D—1948 level of main south quarry; E—remnants of prequarry surface.

destroyed some of the original quarry floor but stopped short of the area which apparently underlay the original site. The remainder of the original quarry floor and the low cliff left by the miners remained untouched until 1947 (Fig. 3) except for small excavations made by Hrdlicka and Broom (Broom and Schepers, 1946, p. 19, 25).

Hrdlicka visited Buxton in 1925 and discovered in the cliff face a cave deposit similar to that which enclosed *Australopithecus* (Fig. 4 A). The deposit was a red, sandy, homogeneous limestone passing obliquely (northeast) through the little hill left by the miners. The trend of the deposit is in general alignment with the reported site of the skull of *Australopithecus*. According to C. L. Camp (personal

communication) the fossil vertebrates found by Hrdlicka were never described and are in the British Museum. In 1937 Broom visited the site and collected more fossils. Broom (Broom and Schepers, 1946, p. 25) refers to the site as "*Australopithecus* Cave"; "Taungs Cave (s)" is widely and loosely used in articles concerning *Australopithecus*.

In 1947 the University of California Expedition began to excavate the Hrdlicka site

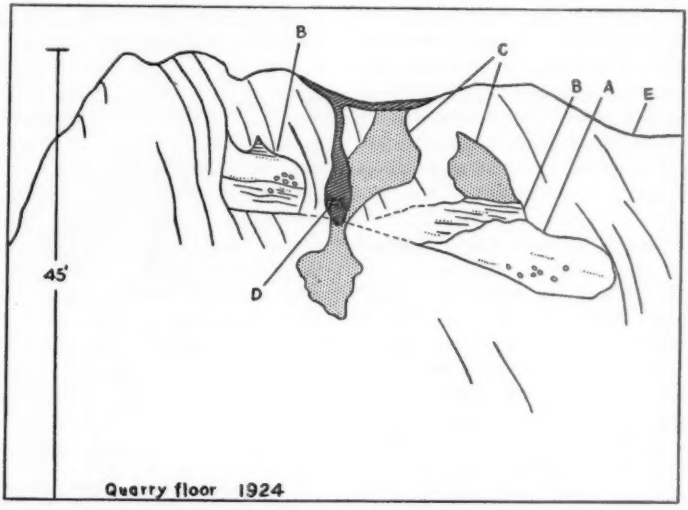

FIGURE 4.—QUARRY FACE IN THABASEEK TRAVERTINE

Showing relationship of original Hrdlicka site (A) to other cave and fissure deposits. *Australopithecus* Cave system (A, B) trends obliquely to right (slightly northeast) away from observer, and generally parallel to escarpment; A—dry phase of *Australopithecus* Cave (Hrdlicka Cave of Broom); B—wet phase of *Australopithecus* Cave; C—sterile, red sand, semicemented; D—unconsolidated black earth bearing Middle Stone Age artifacts; E—prequarry surface.

"Hrdlicka's Cave." Probably this cave is an extension of "Dart's Cave" (named by Broom) which contained the man-ape, the two caves being the same or parallel galleries of one cave system developed along the strike of steeply dipping layers of travertine. Another cave discovered after 1937 and called by Broom "Spier's Cave" was never definitely located by Broom and could not be located by the Californian expedition. Presumably Spier's Cave was close to the others, but relationships are impossible to demonstrate. Hereafter, Hrdlicka's Cave and Dart's Cave are referred to as sites in the *Australopithecus* Cave, for the writer strongly believes, on the basis of field evidence, that the Dart, Hrdlicka, and perhaps the Spier sites were in essentially one continuous cave system. Broom (1948, p. 2) uses the term which was still richly fossiliferous. It was soon discovered that the cliff face preserved a remarkable record of cave and fissure fills (Pl. 3, fig. 1; Fig. 4) which adds much to our knowledge of the occurrence of *Australopithecus africanus*.

A most important discovery was that the cave at Hrdlicka's site is larger than previously suspected and was partly filled first by red sand (the Hrdlicka Cave deposit of Broom; F. E. P. Loc. 38-5 A) and later by nearly horizontal layers of pure lime intercalated with thin, irregular lenses of red, sandy limestone (F. E. P. Loc. 38-5 B). Thus, two phases, a dry and a later wet phase, are represented in superposition. The lime in the upper levels of the Hrdlicka site, as well as in its lower sandy levels, carries quantities of baboon remains.

One concentration in the upper level includes skulls or parts thereof representing at least 10 individuals. The fossils in the dry phase differ in color and in preservation from those in the wet phase, and the matrices differ slightly.

In view of these differences, a statement by Broom (1948, p. 2) concerning the fossil baboons found in the vicinity of *Australopithecus* is quoted:

"... It seems to me that all Haughton's specimens belong to one species, [*Parapapio antiquus*] and further that they are not likely to have been contemporaneous with the baboons [*P. izodi*] from the *Australopithecus* Cave. The matrix is much lighter in colour in Haughton's specimens. Further, the fact that these were discovered probably 5 years before the *Australopithecus* Cave was opened up seems to lead to the conclusion that these baboon specimens of 1920 came from a cave much nearer to the travertine escarpment, and probably belong to a much later date than the remains found in the *Australopithecus* Cave."

Thin-section analysis of the red limestone from the dry phase, the wet phase, and the matrix surrounding the skull of *Australopithecus africanus* (sample supplied by Professor Dart) was made by Miss Ada Swineford, petrographer of the Kansas Geological Survey. She states (written report) that the three samples

"... are mineralogically very similar ... there is nothing to indicate that they are of different ages. All thin sections consist of quartz grains scattered in a calcite (and ankerite?) cement with various quantities of collophane. There are also a few scattered grains of chert (less than 1 per cent of the grains) and feldspar (sodic plagioclase and microcline, less than 2 per cent). The only heavy minerals noted were 1 or 2 zircon grains. The grains [of all kinds] form less than 45 per cent of the rock, and are of very fine sand and coarse silt size. The average grain diameter in A [the dry phase limestone] is about 0.1 mm. The grain size is slightly larger in B [the wet phase limestone] and smaller in C [the skull matrix]. The grains are subrounded to extremely angular. The angularity seems to be due to etching of the grains or partial replacement by the calcite cement. ... In general, I think that many of the original grain surfaces have been destroyed, although some still carry a coating of red iron oxide. The calcite cement is finely crystalline (crystals less than 0.06 mm. in diameter), but all the slides also show areas of coarsely crystalline calcite free from detrital grains."

The evidence from Hrdlicka's site as now known (Fig. 4), combined with the circumstances of preservation noted by Broom, suggest that the cave system containing *Australopithecus* extended for several hundred feet roughly parallel to the escarpment and contained deposits showing a dry and a wet phase. We can account for the frequent discovery of baboon remains by the fact that early quarry operations moved northward along the long axis of the cave system. This is also generally parallel to the outer edge of the travertine; thus, Broom is incorrect in assuming that his specimens were farther from the escarpment than were Haughton's. The evidence from Hrdlicka's site indicates that Broom was probably correct in his assumption that Haughton's specimens of the light (lime) matrix are younger than the specimens of the dark matrix (sandy lime). But, Broom is probably incorrect in assuming that the two species of baboon came from different caves. It is more probable that both species came from different levels in the same cave system and are slightly different in age.

In summary, meager accounts, both published and oral, combined with a personal field study make possible the following story of physical events which include the interment of *Australopithecus africanus:*

(1) The cave system containing the man-ape was developed near the eroded periphery of the Thabaseek travertine, definitely the oldest of the four main travertines at Buxton. Because the cave system is near the periphery, it is certainly in the youngest part of the travertine; the dip of the carapace lime corroborates this. Therefore, the man-ape is younger than most if not all of the Thabaseek travertine. Also, the surface breccia of Stage 1 in the travertine sequence is probably older than the Thabaseek travertine, particularly the carapace lime. Thus, a lower limit can be placed on the relative age of the man-ape with respect to the age of the travertines.

(2) Hrdlicka's site indicates that the earliest deposit in the cave is a massive, red, sandy limestone overlain by pure lime with intercalated, irregular lenses of red, sandy limestone differing little mineralogically from the earlier deposit. The early deposit seems to represent a dry phase and contains remains of turtle, baboon, small antelope, rodent, small carnivore,

crab, and, occasionally, a surface showing what appear to be tracks of small mammals made originally in the soft dirt of a cave floor. The later deposit seems to represent a wet phase and contains only baboon and small antelope. The time interval between the two faunas is undoubtedly short.

The man-ape may have come from the earlier dry phase, as Broom believed (he was unaware of the wet phase), but the cranial cavity of the skull is coated with a clear, drusy calcite, a condition not observed in any of the numerous baboon skulls from the dry phase. Cranial cavities of these baboons are invariably encrusted with reddish iron oxide, and many show secondary solution. By contrast, the equally numerous baboons from the wet phase show drusy calcite like that in the skull of the man-ape. Thus, the mode of occurrence suggests that *Australopithecus africanus* came from the younger, wet phase, not the older, dry phase of deposition in the cave system. Robinson (1953, p. 447) finds similar evidence at Swartkrans.

(3) A later deposit of coarse, red sand, devoid of fossils or artifacts, filled remaining cavities of the cave system and also filled fissures which seem to have been formed after the original cave system (Fig. 4 C). The red sand is massive, only semicemented, and punky. This deposit is definitely truncated by erosion which has dissected the surface of the Thabaseek travertine; thus the deposit is undoubtedly older than the unconsolidated fill of red, sandy earth in the Norlim and Thabaseek travertines.

(4) A pipe, developed by solution, extended from the surface downward and cut into both the travertine and the semicemented sand, the latest deposit in the cave. A black, unconsolidated earth and a number of stone artifacts of Middle Stone Age (F. E. P. Loc. 38-5 C) filled the pipe. Two of the stone blades (Fig. 10 A, B) are nearly duplicates of certain stone blades (Fig. 10 C, D) from the advanced Middle Stone Age of Witkrans Cave. The black earth in the pipe continued upward into a black earth occupying solution depressions in the surface of the travertine. Similar pipe fills are common in the Norlim travertine but are lacking in the younger travertines. The time of deposition of black earth in the Buxton travertines seems to have coincided with the great diversion of the Thabaseek River (Stage 6 in the Buxton sequence).

It is now possible to demonstrate a series of physical events associated with *Australopithecus africanus* and based on geologic, physiographic, and archeological data. The age of the man-ape of Taungs can be satisfactorily placed in the Buxton sequence of events. The man-ape is clearly younger than most if not all of the oldest travertine at Buxton; it is possible that older travertines, for example at Boetsap, still exist along the Kaap escarpment. Even if these existing travertines reflect the cyclic events of the whole of the Pleistocene, which seems unlikely (See section on Correlation), the man-ape of Taungs, if not of Sterkfontein and Makapan, cannot belong in the very early Pleistocene and certainly not in the Pliocene. On the other hand, it is equally clear that the man-ape of Taungs belongs well back among the early events of the Buxton sequence. Although no direct relationship can be demonstrated with the Norlim travertine, the Hrdlicka site demonstrates in the three generations of fills and in the truncated surface of the Thabaseek travertine that the first generation of fills almost certainly antedates the Norlim travertine (Stage 3) and probably belongs among the earliest events of Stage 2 in the Buxton sequence.

One can only speculate as to the position of the original entrance or entrances to the *Australopithecus* Cave.[2] The deposits at the Hrdlicka site (Fig. 4 A, B) trend slightly downward and to the northeast, possibly an indication that the entrance was in the opposite direction. It is doubtful that the two cliffs in the Thabaseek travertine[2] (Pl. 5) existed in the time of *Australopithecus africanus*. Possibly the original entrance or entrances were in the upper surface of the travertine. In any event, the cave itself must have extended at least 500 feet in a generally northeast direction and undoubtedly had many irregularities including

[2] These physiographic features and also the conical hill are reconstructed from eye-witness reports collected from several veteran employees by Oxland. Although perhaps not so conical as shown, the presence of some sort of isolated hill of travertine fits well with concrete evidence that the surface of the Thabaseek travertine has undergone considerable erosion.

ramifying galleries in the manner of the Black Earth Cave in the Norlim travertine. Under these conditions there was probably more than one entrance to the *Australopithecus* Cave system.

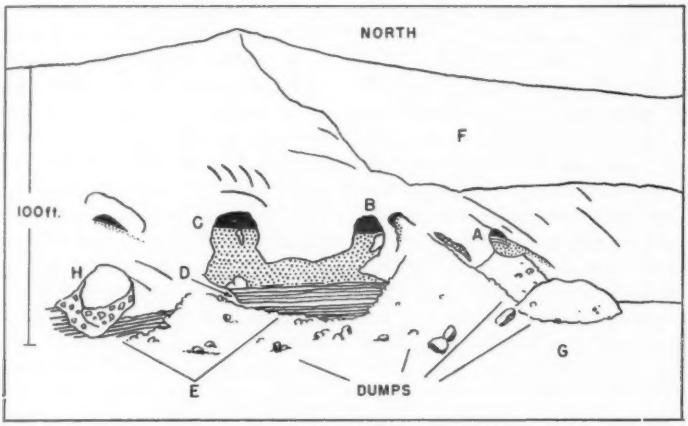

FIGURE 5.—BLACK EARTH CAVE IN NORLIM TRAVERTINE

Showing disconnected galleries of cave system truncated by quarrying; A—gallery containing quantities of vertebrate remains including two distinct types of *Homo;* B—gallery containing thick deposit of ash and vertebrate remains (some charred) in upper level, but no artifacts; C—largest gallery, but sparsely fossiliferous; D—cave floor near bedrock; E—bedrock shales; F—south half of main north quarry; G—floor level of main south quarry; H—remnant of talus with manganiferous surface zone.

Black Earth Cave.—The most important cave deposit at Buxton other than that which contained *Australopithecus africanus* is definitely younger and can be related to a particular physiographic event in the history of the Buxton travertines. When the Thabaseek River cut a canyon through the Norlim travertine (Stage 4) it intersected a large cave system (Pl. 3, fig. 2; Fig. 5). As is generally true of caves and fissures in the travertines, this one had developed roughly along the strike of steeply dipping layers of lime. The Black Earth Cave extended down to a broad, level floor near but not on the bedrock. The upper reaches of the cave ramified through the travertine.

Before the cave system was intersected by the canyon, several feet of nearly pure lime was deposited in horizontal layers on its floor. Upon the pure lime and with little intergradation was deposited approximately 16 feet of dark-red earth, sandy and fluviatile below, and grading up into finer, nonfluviatile material at the top. Rotted blocks of travertine are included in the upper layers of the deposit. The abrupt change from pure lime to sand probably indicates the time of intersection of the cave system by the Thabaseek River.

In the prequarry surface, the cave must have had its main entrance, or entrances, in the north wall of the canyon cut through the Norlim travertine. Quarry operations had destroyed the entrance and most of the fossiliferous deposit before 1947. Duplessis (personal communication) reported that great quantities of bone had been thrown on the dumps, and that eventually this section will be completely destroyed.

Isolated galleries of the upper part of the cave system were exposed, as well as a number of fossiliferous nooks and crannies in the travertine that are not shown. The galleries trended downward from the entrances; this fact plus the observed position of the fossils indicates that the original cave entrance (or entrances) was somewhat higher than the position of galleries illustrated.

Galleries A (F. E. P. Loc. 38-14) and B (38-18 A) were richly fossiliferous, gallery C (38-18 B) much less so; none was definitely

implementiferous, although a bone awl was discovered. Gallery A exhibited three zones in the fossiliferous fill which had a maximum thickness of 5 feet. The lower 2 feet consisted of a mash of leached and rotted bones and teeth in red and black streaked clay. Toward the lower limits of this zone fossils were absent, and thick, irregular veins of clear crystalline calcite became prominent. The latter occurred still farther down in sterile black earth below the 5 feet of fossiliferous earth. The calcite veins reached a maximum thickness of 1 inch and formed sloping sheets of crystals curiously interlayered in the soft earth. Presumably the calcite was derived from the leached fossils immediately above.

An overlying zone 2 feet thick contained great quantities of hyaena coprolites as well as bones and teeth (including fragments of two types of *Homo*) well preserved but red like the leached fossils below. (*See* faunal list.) Above this zone 15 inches of dusty black earth, ash-bearing in part, contained light-colored bones and teeth of recent appearance. Horn sheaths still remained on some of the horn cores of ungulates. Complete skulls of the jackal, the hunting dog, and the antelope were found, and, significantly, coprolites were lacking. Where coprolites are common, associated bones are usually broken and badly splintered. This indicates a hyaena den.

Gallery B contained a fossiliferous equivalent of the two upper zones of Gallery A, but the stratigraphy was confused because of slumping and the presence of large roof blocks of travertine. The upper zone yielded quantities of charred bone and a bone awl but no other sign of human occupation except for the high ash content of the black earth.

Gallery C was sparsely fossiliferous but afforded the maximum (16 ft.) section of fill in the Black Earth Cave. A single chip of ostrich eggshell with curving lines scratched on it indicates the Wilton culture of the Late Stone Age of Africa. However, the position of the eggshell relative to the upper and lower zones of Galleries A and B could not be determined.

The Black Earth Cave apparently was the den of hyaenas when first inhabited; these beasts are probably responsible for the astonishing representation of ungulate mammals and also for the human remains in the lower fossiliferous zones. At least one species—a giant species of *Equus*, possibly *E. capensis*—in the lower zones is definitely an extinct form. The upper fossiliferous zone yielding charred bone and complete skulls probably represents a time of human habitation, but the absence of stone tools is puzzling. It is hoped that a C^{14} count may be had from the charred bones.

It is clear that the cave itself was developed in the Norlim travertine prior to the cutting of the canyon, and that, upon transection, it began to fill with sand and other detritus. The first occupancy by carnivores (presumably hyaenas) must have been considerably later. The decorated eggshell and bone awl suggest Late Stone Age for at least the upper fossiliferous zone, but one must turn to physiographic evidence to relate the cave fossils to the travertine sequence.

A small patch of semiconsolidated talus left by the quarrymen (Fig. 5 H) is genetically related to the talus described in Stage 3 of the travertine sequence and demonstrates that a talus slope existed at the foot of the steep north wall of the canyon and hence below the original entrance to the cave. It is possible that at first the cave opening was too high on the sheer cliff and that a talus had to form before the cave could become accessible and attractive to the first inhabitants (probably hyaenas) responsible for the collection of bones and teeth. By this reasoning, the first occupancy of the cave was not earlier than the formation of the talus slope in the canyon and probably followed the formation of the Oxland travertine (Stage 4), slightly before or contemporaneous with the formation of the Channel alluvium. When the alluvium was forming, probably under swampy conditions, the canyon must have been an attractive and secluded watering place for many kinds of mammals including man and especially ungulates living in the broad Harts valley. It is unlikely that hyaenas occupied the Black Earth Cave at the same time that Wilton peoples occupied Powerhouse Cave, for the latter was not available to man until some time after the great diversion of the Thabaseek River.

Powerhouse Cave.—The final diversion of the

Thabaseek River exposed a subterranean channel in the apron of the Norlim travertine (Stage 5) and thus provided an easily accessible and comfortable shelter for human occupancy

designs executed in red pigment; the one clear design noted is a five-rayed asterisk. These designs are the only ones discovered in the caves of the Kaap escarpment.

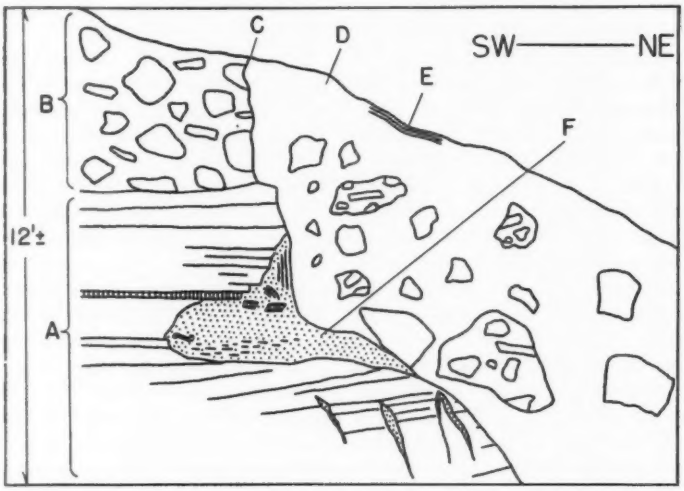

FIGURE 6.—SECTION IN SOUTHWEST WALL OF CANYON CUT THROUGH NORLIM TRAVERTINE

(*see* Pl. 2, fig. 1D): A—Precambrian bedrock; B—older surface breccia deposited on fresh bedrock of original Thabaseek channel; C—southwestern wall of canyon cleanly incised through Norlim travertine into older breccia and bedrock; D—semicemented talus of reddish, sandy lime containing pebbles, cobbles, and boulders of bedrock and older breccia; E—surface zone of manganiferous lime developed on present surface of talus; F—small cave or shelter filled with cemented, cream-colored, sandy limestone containing small, "floating" roof blocks, unidentified bone fragments, and some drip lime. Deposit evidently cemented sometime before canyon was fully eroded.

(Pl. 5; Fig. 2). The cave (F. E. P. Loc. 38-27) is in the east wall of the present river channel and high enough (15–20 ft.) above the channel bottom to insure against flooding. Westward extensions upslope from this subterranean cavity appear high in the opposite wall of the river channel. The mouth of Powerhouse Cave is approximately 50 feet wide at its maximum and has a high ceiling permitting plenty of head room; but within 20 feet it pinches down to a narrow gallery leading farther back to a wide space but one with a ceiling too low for habitation. The cave mouth provides approximately 700 square feet of shelter; this space is now covered with dusty, blackish earth, apparently wind blown, ranging up to 28 inches thick. This is the area of principal occupation. Walls of the shelter have faint

Because Powerhouse Cave is primarily an implementiferous site, Camp and the writer excavated only a few test pits and presented all the material to the Archaeological Survey of South Africa. Dr. A. S. Brink (Bernard Price Institute for Paleontological Research) has kindly provided a preliminary check list of vertebrates found in the cave deposit (Table 1). The artifacts include elements only of the Wilton culture of Late Stone Age.

Powerhouse Cave is important because it provides a rough check of physiographic evidence of age against archeological evidence. The cave could not have been available to habitation until the last diversion of the Thabaseek River transected the Norlim apron. That diversion destroyed part of the Oxland travertine; thus, the latter is clearly older than

the cave. The Thabaseek channel had to be cut down far enough to make the cave safe from flooding. Since the implementiferous earth in the cave shows no sign of water action, habitation began only after the river channel had eroded to approximately its present form. This suggests that the cave was accumulating a Wilton culture during Stage 7, the last stage in the travertine sequence. It might be presumed that the Norlim apron was transected earlier by a tributary of the Thabaseek, but the channel is obviously one which could have been cut only by the Thabaseek, and then only when diverted as described.

Miscellaneous localities at Buxton.—Several sites in caves, pipes, and on the surface of the Buxton travertines are of secondary importance but are worth recording because they have been destroyed.

BLUE POOL CAVE: High in the truncated north face of the Oxland travertine, and overlooking the Blue Pool (Pl. 4, fig. 1), was a small cave (F. E. P. Loc. 12), since destroyed. Twenty-seven feet of trenching in the floor of the cave exposed a section 5 feet thick. The lower 2 feet was composed of unconsolidated, fluviatile sand containing bits of charcoal and occasional bones of small vertebrates. Above the sand occurred approximately 1 foot of blocky soil, dark blue-black with red streaks, and above this 1 foot of cream-colored, chalky lime carrying thin lenses of fluviatile sand. The uppermost 12 inches of the deposit was composed of a brown earth overlain by black earth, with a superficial layer of dust and manure. The upper 6 inches contained splintered long bones of ungulates, bits of ostrich eggshell, and matted bones of small mammals and birds undoubtedly concentrated originally in owl pellets. Ashes and charred bones also occurred in the upper 6 inches.

The cave deposit below the upper 6 inches appears to have been mainly fluviatile, hence the cave was not suitable for habitation during most of its existence. The cave deposit undoubtedly accumulated as the Thabaseek River truncated the Oxland travertine and eventually isolated the cave and its deposit high on the face of the cliff. Subsequent rock falls permitted fairly easy access to the cave.

The charred bones and fragments of ostrich eggshell in the superficial layer of the deposit suggest that Wilton peoples occasionally used the cave. However, its position overlooking the eery depths of the Blue Pool possibly did not appeal to superstitious peoples, especially as the Powerhouse Cave downstream offered more comfortable shelter.

It seems reasonable to relate the fluviatile deposit of Blue Pool Cave to Stage 6, the superficial deposit indicating habitation to Stage 7 of the travertine sequence.

In 1952 Malan sent a written report by Dr. Philip Tobias, describing another cave deposit of Late Stone Age in the Oxland travertine. Quarrying showed that the cave was in the western periphery of the travertine and opened westward onto the old Thabaseek channel. (In 1948 the writer inspected the many recesses along the western periphery with special care because of the many stone chips occurring there, but found no superficial evidence of a cave entrance.) The unconsolidated deposit reported by Tobias contained many bones and teeth of baboon, man, lion, and smaller carnivores, antelope, and warthog. Included was a "small, partly mineralised, pentagonid" calvarium (frontal and parietal bones) of Bushman type. Associated with the remains were many artifacts of Smithfield type, including end and side scrapers, a grooved stone, slender bone awls, and beads and fragments of ostrich eggshell. This discovery adds another interesting chapter to the Buxton sequence and further strengthens the conclusion that the Oxland travertine antedates the Late Stone Age of South Africa. Probably the bulk of the Blue Pool Cave deposit, and the newly discovered deposit in the Oxland travertine, antedate the culture of Powerhouse Cave.

OCHRE CAVE: This cave (Pl. 5), 800 feet south of Powerhouse Cave, merits comment only because it may have provided the Wilton people of Powerhouse Cave with a source of pigments (F. E. P. Loc. 38-19). The floor of the cave is only 4 feet above the bed of the Thabaseek River, so that in spite of ample dimensions (60 ft. long, 8 ft. wide, 9 ft. high) the cave was and is unsuited for habitation because of the hazard of flooding. The cave was developed in bedrock dolomite along a joint plane trending northeast. At present, the mouth

DIAGRAMMATIC PANORAMA OF KAAP ESCARPMENT

Showing travertines before quarrying operations began. View looking northwest. Scale shown by church in circle; distance from Ochre Cave to Blue Pool is 0.8 mile.

opens at the base of a low cliff directly onto terraced basins usually filled with water.

Four test pits excavated in the cave floor exposed a veneer of dusty, rubbly earth approximately 1 foot thick, containing many cores and flakes of the Middle Stone Age. All such artifacts found in place were well within 50 feet of the prequarry surface, but bones and teeth were found as deep as 100 feet where the Norlim overlaps the Thabaseek travertine.

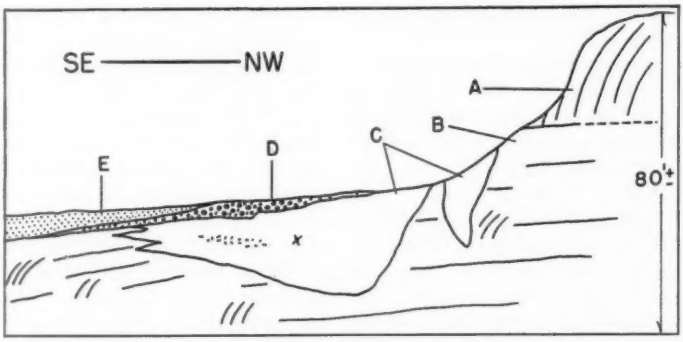

FIGURE 7—SECTION THROUGH APRON OF OXLAND TRAVERTINE

Showing: A—carapace lime; B—apron lime; C—semicemented fissure (?) fill containing zone of bone fragments and cheek tooth of small *Equus* at X; D—cemented cobbles; E—Channel alluvium. Horizontal scale reduced ½.

cobbles and pebbles of black chert and iron shale altered partly to yellow and red ochre, respectively. Some pieces had plane surfaces as though ground for pigment. A few stone flakes of Late Stone Age occur. A few bones and teeth of bush pig (extinct in the region), antelope, porcupine, and smaller rodents also occur. Ostrich eggshell is lacking.

The deposit in Ochre Cave probably belongs in Stage 7 of the travertine sequence, even though the age of the cave as a subterranean cavity cannot be placed because it is in dolomite and is isolated from the travertines. However, the present cliff face is surely related to the transection of the Norlim apron by the Thabaseek River. Thus, the cave as now exposed must have been a consequence of the last diversion of the Thabaseek—Stage 6 in the travertine sequence.

RED EARTH PIPES: The Thabaseek and Norlim travertines are riddled with pipes and fissures filled with massive, unconsolidated, red, sandy earth. It extends from the surface down to at least 100 feet. Lack of bedding planes indicate that water action was not important in its deposition. In the earth occur sporadic remains of vertebrates, and stone Also, the artifacts occur exclusively in the Norlim travertine except for the pipe fill in the Thabaseek travertine at Hrdlicka's site (Fig. 4 D). However, this fill is more black than red, and the artifacts are more advanced than any from the Norlim pipes and fissures. No artifacts were found in the fills of red earth in the Thabaseek travertine, but there was less chance of finding any in its few remnants. This travertine had more fissures and pipes than the Norlim travertine and contained three generations of red earth fill—the earliest surely the *Australopithecus* Cave deposit, the latest the unconsolidated red earth found also in the Norlim travertine. Both travertines contain fills of still younger black earth.

OPEN SITES: Stone artifacts indicating Middle and Late Stone Age occur generally over the surface of the travertines and bedrock of the Buxton area. As a rule such open sites have little importance for dating the travertine sequence. However, three occurrences merit description. (1) Stone flakes of the Middle Stone Age (Pl. 2, fig. 3) occur on the apron of the Oxland travertine, covered by the Channel alluvium. This undisturbed occurrence lends importance to the fact that

artifacts of similar type occur uncovered on the west flank of the carapace of the Oxland travertine. (2) A trimming stone of Late Stone Age was found in the upper part of the Channel alluvium. (3) A few flakes of stone and pieces of ostrich eggshell were found in shallow fissures in the northeast side of the Oxland travertine.

These occurrences indicate that the Oxland travertine is definitely older than the artifacts of Middle Stone Age occurring at Buxton, but that the artifacts generally have a surface distribution contrasting significantly with the fissure distribution of similar types of artifacts in the Norlim travertine. Only artifacts of Late Stone Age are found in the few fissures developed in the Oxland travertine. Thus, the Channel alluvium is certainly younger than the Oxland travertine on archeological as well as geological evidence, and cannot be an older lake deposit accumulated behind a dam of Norlim travertine (Stage 4).

Other Fossiliferous and Implementiferous Localities along the Kaap Escarpment

Witkrans Cave

One of the most interesting and significant cave deposits on the Kaap escarpment was discovered by a Buxton schoolboy, "Saakie" Hayward (Pl. 3, fig. 3). As a result of curiosity inspired by part-time employment with the expedition, Master Hayward found remains of fossil baboons in the rubble below a small travertine cliff 3 miles south of Buxton (F. E. P. Loc. 43). This travertine is briefly described by Young (1925, p. 59). The fossils came from a ledge jutting out high on the cliff. The ledge proved to be the cemented floor of an old cave which through erosion had lost most of one wall and the roof. The cave floor projected as a small but prominent ledge on the face of the cliff of travertine (Fig. 8 A) and contained a rare record of man, his culture, and contemporary vertebrates representing a part of the Middle Stone Age of South Africa.

The white cliff called "Witkrans" is the southernmost remnant of a small mass of travertine built out from the vertical cliff of dolomite which forms the escarpment. Active deposition of lime apparently ceased with the cementing of the cave deposit of Middle Stone Age. Since that time erosion has caused the collapse and removal of much of the carapace lime and has divided the original mass into two parts (Fig. 8).

HISTORY OF WITKRANS CAVE: A number of solution caves developed in the Witkrans travertine probably before erosion of the mass. The largest cave developed in the travertine close to and paralleling the dolomite cliff. At present this cave is a large grotto open at both ends (Fig. 8 B) and is the home of a pack of baboons. A layer of rubble and manure covers the floor at the south opening, and older deposits may lie beneath. The cave containing a record of the Middle Stone Age developed near the periphery of the travertine in hemispherical layers of carapace lime and thus had a semicircular floor plan. The entrance seems to have opened southward. The cave was hall-like and curved north and west, narrowing and ascending to a hidden opening above the ceiling of the grotto. At present, cool air and, following exceptionally heavy rains, water flow out of the constricted opening at the back of the cave. At intervals, reported locally to be 15 years or so, heavy rains falling on the Kaap plateau may so saturate its surface that a sheet flood pours over the escarpment. The streams become torrents and at many points along the escarpment water cascades over the dolomite cliffs. Such a flood was experienced at Buxton in early 1948; Oxland reported that he saw water spurting strongly from the opening at the back of Witkrans Cave.

After Witkrans Cave was fully formed, a source of water high up in its north wall began to deposit a cone of lime which built out and covered most of the original floor (Fig. 9). Formation of the cone was ended by a new phase of deposition which resulted in a poorly cemented accumulation of water-worn cobbles of dolomite and slabs of shale grading upward into less coarse detritus. The cementing of this deposit appears to have been at least in part contemporaneous with the accumulation, and the latter probably signalled the beginning of the erosion which has destroyed much of the original travertine.

Approximately 5 feet of sterile detritus accumulated in the cave before it became inhabited by vertebrates. At this time the detritus formed a fairly level floor 6 feet wide with more than 8 feet of head room between the floor and vaulted ceiling. The floor sloped gently (6°) toward the front entrance. Under these conditions habitation of the cave began. An additional 12–14 inches of detritus accumulated but was mixed with quantities of bone, teeth, and stone artifacts of the Middle Stone Age. A thin sublayer 1–2 inches thick (Fig. 9 B) contained only bones and teeth, and a definite zone of parting limited it above and below. The upper, and main producing layer (Fig. 9 C), was in part very solidly cemented and presented an upper surface studded with bones and teeth; the whole was covered with a black, manganiferous "varnish", perhaps related chronologically to the similar black zone on the apron of the Oxland travertine and elsewhere at Buxton.

Several areas lacking cementation were found in the main producing layer. That this layer was a real unit and was not pocketed with younger detritus represented by the uncemented areas is indicated by these facts: (1) the artifacts and bones individually extended from the uncemented into the cemented area; (2) transition between cemented and uncemented areas was evident; (3) bones and teeth, whether in the cemented area or not, are thoroughly petrified and look like the bones and teeth in the cemented areas; and (4) uncemented areas exhibited rotting of the lime and of the fossil bone. Some specimens of teeth show solution cavities in the enamel. With one exception (below), the zones of little or no cementation were sealed over with a layer of lime containing black laminations and a surface "varnish".

The cemented and varnished surface of the deposit from the Middle Stone Age ends the principal chapter in Witkrans cave. However, in the back of the cave, protected by a remnant of the vaulted ceiling, there was scanty

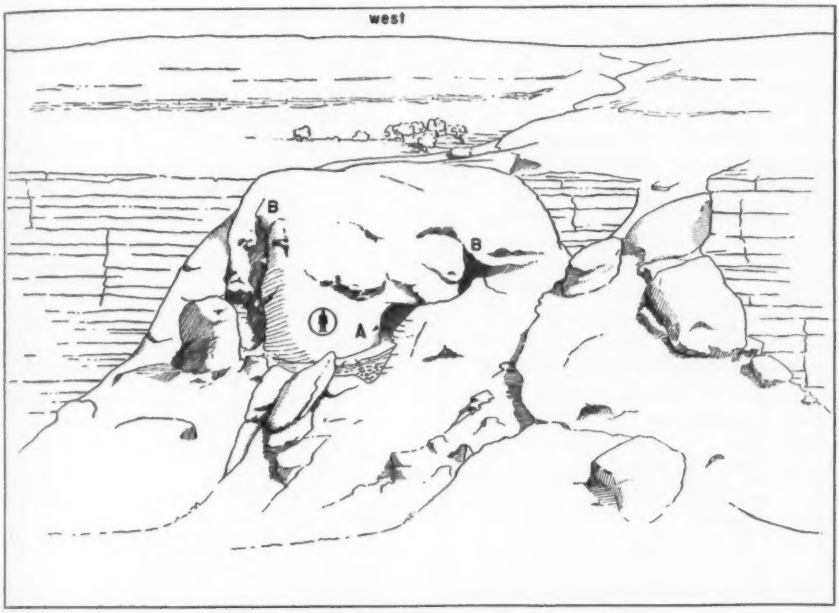

FIGURE 8.—SOUTH HALF OF WITKRANS TRAVERTINE

Showing: A—unroofed cave containing deposits of Middle and Late Stone Age ; B—baboon grotto open at both ends. Human figure in circle indicates approximate scale.

but definite evidence of a culture of the Late Stone Age. A thin wedge of light-brown, dusty rubble (Fig. 9 D) overlay the cemented floor with its surface "varnish" and graded upward

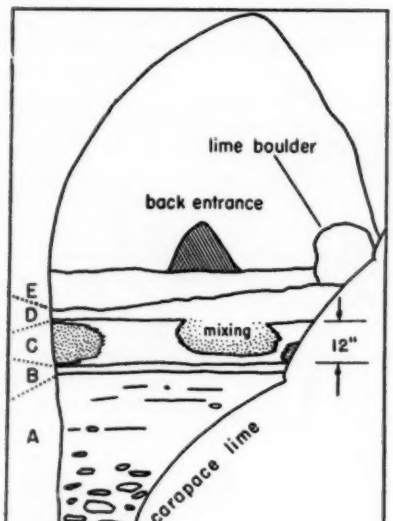

FIGURE 9.—DIAGRAMMATIC CROSS SECTION OF DEPOSITS IN WITKRANS CAVE

A—sterile agglomerate; B—fossiliferous but no artifacts; C—richly fossiliferous and implementiferous deposit of Middle Stone Age; D—sparsely fossiliferous and implementiferous deposit of Late Stone Age; E—recent rubble and manure.

into a black rubble (Fig. 9 E) containing fresh manure of baboon and hyrax. The light-colored deposit contained a few worked flakes of stone and chips of ostrich eggshell, some fashioned into beads. This deposit, small as it was, overlay an uncemented and disturbed pocket in the producing layer of the Middle Stone Age. The pocket may well have been a pit excavated by the later inhabitants, but it seems more likely that an uncemented pocket in the Middle Stone Age layer did not have a surface veneer of lime strong enough to prevent mixing of the later with the earlier deposit. The pocket was certainly filled partly by the light-colored rubble and contained a mixture of Middle Stone Age and Late Stone Age artifacts and also pieces of ostrich eggshell. The latter were absent in the undisturbed layer of the Middle Stone Age.

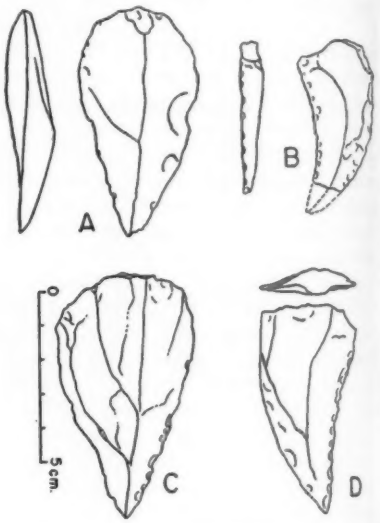

FIGURE 10.—SELECTED ARTIFACTS OF MIDDLE STONE AGE

From black earth pipe at Hrdlicka site (A and B), and from Witkrans Cave (C and D) indicating contemporaneity.

There is little evidence as to the exact time of collapse of the wall and roof of the Witkrans Cave although it obviously took place after the Middle Stone Age deposit accumulated and was cemented. The rubble in the back part of the cave was of such small areal extent that it bore no demonstrable relation to the Middle Stone Age deposit, which indicates that it accumulated before the wall and roof fell away. However, a lime boulder which rested on the light-colored rubble may indicate a collapse of the roof after the rubble accumulated. With the disappearance of the roof and wall the exposed floor would have been stripped rapidly of the unconsolidated rubble except where it was protected at the back of the cave.

Malan (personal communication) confirms the writer's opinion that the flakes and blades of the Middle Stone Age of Witkrans (Fig.

10 C, D) are thinner and the technique noticeably more advanced than the artifacts from the fills of red earth in the Norlim travertine or from the surface of the Oxland travertine. Also advanced are the artifacts from the black earth fill at Hrdlicka's site (Fig. 4 D) in the Thabaseek travertine of Buxton. Two of numerous stone blades from Witkrans showing advanced technique are nearly duplicated by two of several blades found at the Hrdlicka site (Fig. 10 A, B). It seems reasonable to correlate the two occurrences since both are unique in the region, according to John Power (McGregor Memorial Museum, Kimberley), a collector of artifacts from the Kaap plateau and escarpment.

The superficial layer (Fig. 9 D) at Witkrans is confidently correlated with Little Witkrans, Powerhouse Cave, and Blue Pool Cave deposits on the basis of the Wilton artifacts of Late Stone Age.

Little Witkrans

A small cliff of travertine at the edge of the Kaap escarpment 0.3 mile south of Witkrans (Pl. 4, Fig. 4) forms a shelter under which has accumulated a deposit of Late Stone Age (F. E. P. Loc. 40). Deposition of lime probably ceased when the stream channel which nurtured the travertine was shunted northward. At present, the travertine cliff is approximately 50 feet high and 150 feet long. No caves occur in the travertine, but erosion has developed, at its base, a recess having a protecting overhang of carapace lime. The recess is shielded from the south by great boulders of travertine slumped down from the receding cliff. The recess forms a snug shelter 12 feet deep and approximately 30 feet wide, and the ceiling allows 6 feet of head room. The earthen floor is level, and from this vantage point one has an unrestricted, somewhat elevated view of the broad valley of the Harts River.

The shelter deposit covers at least 450 square feet, has a maximum thickness of 4 feet, and is unconsolidated except for a zone of fine to coarse agglomerate 6 inches thick on bedrock. Sampling trenches 3 feet wide, totaling 33 feet in length, were excavated employing 12-inch vertical intervals or less. The deposit accumulated under predominantly dry conditions, but a thin layer of crusty, white, limy earth 14 inches below the surface indicates a temporary wet period in the shelter. This layer resembles lenses of chalky white earth noted in the floor of the Blue Pool Cave. The uppermost 12 inches of the floor has a high content of ashes and also produces most of the artifacts. The upper 3 feet of the deposit yielded a fine collection of artifacts characterized by microliths, some beautifully worked in clear crystalline quartz, beads, and decorated pieces of ostrich eggshell. A few scattered bones, some charred, and teeth occur also. According to Malan (manuscript), the artifacts represent a typical microlith industry of South Africa—that is, the Wilton culture of the Orange Free State.

The lower 6 inches of the deposit differs from the earth above in being a semiconsolidated agglomerate of sand and cobbles. A number of angular rock fragments from this level seem to have been worked and suggest a culture different from that in the upper layers.

Thoming

The only major body of travertine along the 35-mile stretch of escarpment between Boetsap and Buxton is at Thoming, 4 miles south of Buxton (F. E. P. Loc. 39). Here, a cliff of travertine 1 mile long stands out from the dolomite. The cliff face is actively receding even though there are perennial springs above and below the travertine. The stream channel running off the escarpment splits and runs around the north and south ends of the travertine. Reconnaisance revealed no significant cave deposits although there are small caves haunted by bees and baboons in the southern half of the cliff.

In 1947 the Northern Lime Company had begun to quarry the north end of the travertine, and in so doing had developed an excellent section exposing both the carapace and apron. At least at the north end, the carapace lime lacks the fissures and fissure fills of the Thabaseek and Norlim travertines of Buxton and therefore is probably younger. Lithologically, the Thoming lime at its northern

end is most similar to the Oxland travertine at Buxton. The latter also lacks the fissures and fissure fills of the older travertines. Unfortunately, the writer was unable to search for a surface zone of black laminations such as occurs on the apron of the Oxland travertine.

Incorporated in the carapace lime at Thoming are many plant molds and impressions—leaves, stems of reeds, and mosses—resulting from encrustation by lime. C. L. Camp reports that a preliminary survey of the plant fossils (by Dr. Robert Rodin, botanist of the expedition) shows that there is some evidence that a slightly different climate prevailed when the travertine was being deposited. Two of 13 species of plants identified from the Thoming travertine do not occur at present at Thoming but do occur at Gladysvale near Krugersdorp, under somewhat wetter conditions. No fossil vertebrates were found at Thoming although quarry men stated that bones are sometimes found in the carapace lime.

Boetsap (Fossil Hill)

The Kaap escarpment in the vicinity of Boetsap is veneered with a widespread layer of vlei travertine which tends to be rubbly and forms few cliffs (Fig. 11). Locally, as at Tiger Kloof a short distance southwest at Boetsap, small cliffs of travertine occur. The main travertine sheet extends several miles east, west, and south from Boetsap and has been test-drilled for commercial purposes.

Marginal areas of the travertine near the escarpment, and underlying Precambrian shales, have been deeply scalloped by tributaries of the Harts River. Near Tiger Kloof two small hills of shale capped with travertine stand isolated half a mile from the main mass of travertine (Pl. 4, fig. 3). Likewise, Fossil Hill, locally known also as "Lion Head," is isolated from the main travertine (Fig. 11).

The only known fossils from the Boetsap travertine occur in the western side of Fossil Hill, approximately 2 miles southeast of Boetsap and 1 mile northeast of the Boetsap-Klipdam road (F. E. P. Loc. 42). The fossil deposit has been known since the days of Livingston, but the fossils collected (mostly by Professor R. B. Young and students) from here have not been described, and their present whereabouts is unknown. The University of California expedition found several cubic feet of the deposit containing remains of horse, pig, artiodactyl, and plants, but no primates and no artifacts. This material was collected by the expedition and is now at Berkeley, California.

Conditions attending the accumulation of the fossils, and physiographic events following their accumulation have an interesting and important bearing on the relative geologic age independent of any bearing which the fossils themselves may have. The deposit consists of broken bones, teeth, and occasional coprolites, packed closely together in a layer approximately 1 foot thick. The remains are thoroughly petrified. The deposit is limited laterally by vertical surfaces of cave walls. Pure lime, cream-colored and slightly sandy here and there, solidly cements the deposit. Carapace lime dipping eastward seals the deposit from above. These facts indicate that a cave was developed in the Boetsap travertine and was frequented by carnivores, probably hyaenas. There accumulated a thick litter of bones, teeth, and coprolites, which was then cemented and sealed by lime-bearing waters. Cementing and sealing could have occurred only before erosion isolated Fossil Hill and while the lime was still being actively deposited from a western source. The absence of red sand in the deposit contrasts strongly with the older cave deposits of Buxton.

Since the time when the cave was sealed, the escarpment has receded, and the site has become isolated from the main body of travertine. The active erosion which caused this abated, and a thick alluvium accumulated in the shallow valleys surrounding Fossil Hill. A system of gullies (sluits) probably caused by overgrazing[3] is now actively cutting the alluvium. A few artifacts of stone are scattered about on the alluvial surface, but a search of the extensive gulley system failed to uncover any artifacts buried in the alluvium. Should future investigators find artifacts in place in the alluvium such finds might determine the

[3] Veteran residents at Boetsap report that the gulley system has developed in the last 40 years.

minimum age of the cave deposit of Fossil Hill.

Physiographic and geologic evidence indicate that the mammals of Fossil Hill are of considerable antiquity, possibly dating from early Pleistocene time and antedating the invasion of red sand into the region. Certainly the isolation of hills capped with travertine as observed at Boetsap is not found elsewhere along the Kaap escarpment from Gaap to Vryburg. The nearest approach to this topography apparently existed in the prequarry surface of the Thabaseek travertine at Buxton.

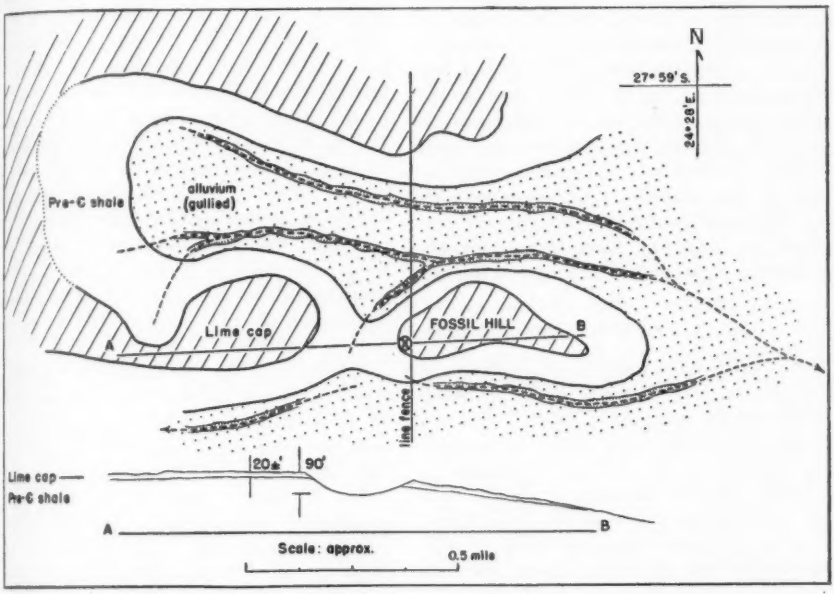

FIGURE 11.—SKETCH MAP OF AREA AROUND FOSSIL HILL NEAR BOETSAP

Showing progressive isolation of travertine as Kaap escarpment recedes westward. Gulley system is more sinuous than shown.

Gaap

Extensive thick travertines of cliff-forming type exist on the escarpment at Gaap, a locality on the Kimberley-Koopmansfontein road. The travertine is being rapidly worked by modern methods by the Union Lime Company. In 1948 a working face was well established in the lime cliff; the face was approximately 100 feet high and presented an excellent cross section. A cursory examination indicated that this travertine is relatively young, is comparable to the Thoming travertine, and contains none of the extensive fissures, caves, and fills found in the older travertines of Buxton.

The Union Lime Company has made an economic survey of the Gaap travertine based on extensive data from numerous bore holes and from a detailed topographic map (Oxland, personal communication).

Iscor

An abandoned quarry 5 miles north of Buxton marks the site of an ancient body of travertine built out from the south side of a canyon sharply incised in the edge of the Kaap escarpment (F. E. P. Loc. 41). Deposition of the cliff-forming travertine progressively blocked the river channel and caused the latter to shift northward. The channel now loops around the position of the travertine in a pattern demonstrating the blocking and

shunting of a river channel by a growing mass of travertine.

Quarrying by the Iscor Company has removed nearly all the lime, leaving several working levels with fringing dumps. Thus, it is impossible to reconstruct the history of this travertine. Fossiliferous cave breccia is common in the retaining walls still standing around the area; from this source and from the dumps a small collection of fossil mammals was made. No fossiliferous deposit was found in place. Judging from the amount and character of cave deposits in the retaining walls and dumps the Iscor travertine originally contained an important fossil record, possibly comparable to the older travertines of Buxton.

Fauna

The variety and occurrence of vertebrates in the principal cave deposits along the Kaap escarpment are indicated in Table 1. This is a preliminary census taken during preparation and curation of the extensive collections at Berkeley. (Species described by Broom from the *Australopithecus* Cave are represented.) Some of the species listed, for example, *Australopithecus* and associated baboons from the *Australopithecus* Cave, and a giant horse from Black Earth Cave, are extinct; certain other species, for example a small owl from the *Australopithecus* Cave and a raven from Black Earth Cave, appear to be extinct in South Africa; many other species, such as the rhinoceros, horse (zebra), lion, and hunting dog are extinct in the region of the Kaap plateau. The occurrence of *Equus* at Boetsap is of particular interest because geologic and physiographic data suggest that the Boetsap fauna is somewhat older than the *Australopithecus* fauna. This occurrence coupled with the evidence that *Equus* and australopithecines of the Sterkfontein region are probably contemporaneous (although not usually associated) has a critical bearing on any discussion of the age of the Australopithecinae. (*See* section on Correlation.)

Detailed study of the fauna listed here may prove to be most interesting and critical for a full understanding of the Quaternary of South Africa.

Correlation

The travertines of Buxton represent a remarkable sequence of events which begin far back in the Pleistocene epoch of South Africa. To some extent this sequence may be correlated with the cave deposits, fossil faunas, and archeological specimens of Buxton. Ideally, further study of the faunas and extended petrographic analyses should be made in order to place correlations on a sound basis; but one can see enough of the overall picture now to justify tentative correlations not only within the Buxton area but with other travertines and associated phenomena along the Kaap escarpment, and, most importantly, correlations with the pluvial-interpluvial sequence represented by the diamond gravels of the near-by Vaal River.

Correlation within the Buxton area presents several problems, but none casts serious doubt on the essential sequence of four main travertines and intervening periods of channel cutting. The early history of the Thabaseek travertine is obscure and is possibly more complicated than indicated in the present synopsis. Significantly, the history of the Older Gravels of the Vaal River is correspondingly obscure—one can only be certain that there are phases yet to be recognized. The oldest part of the Thabaseek travertine seems to be that part overlapped by the Norlim travertine. At present, there is no definitive contact where the younger travertine overlaps the older. Evidence for the separate identity lies in the difference of the dip of carapace lime, in the topographic relationship, and in the relatively greater amount of surface erosion and internal fissuring of the Thabaseek travertine. The absence of a linear contact is not surprising because of the basic chemical similarity of the two travertines and the marked amount of secondary solution and secondary cementation that has taken place in these older travertines.

On the basis of available information it is not certain that the Thabaseek travertine shunted the original channel of the Thabaseek River northeastward to the present position of the canyon in the Norlim travertine; but, judging from the frequent occurrence of

shunting elsewhere along the escarpment, possibly this did happen. One cannot state definitely that a period of channel cutting indicative of increased humidity occurred in the interval between the formation of the Thabaseek and Norlim travertines. Nevertheless, it is clear that erosion has definitely lowered the surface of the former but not of the latter.

The canyon in the Norlim travertine clearly antedates the Oxland travertine, but the exact age of the talus at the foot of the canyon walls, and of the Channel travertine and Channel alluvium, is less clear. Although the talus cannot be traced under[4] the Channel alluvium, the latter is unquestionably younger, for it lies on the Oxland apron which is veneered with a black, manganiferous coating similar to the one of the talus. The question remains whether the talus slightly antedates, postdates, or is contemporaneous with the Oxland travertine. The fact that the talus has been cemented into a tough, punky mass with a veneer of manganese like that on the Oxland apron suggests that the talus is approximately the same age as the bulk of the Oxland travertine. The fact that the talus resembles the fissure deposits in the Oxland apron (Fig. 7 C) and may have required the upstream protection afforded by the Oxland travertine in order to accumulate undisturbed suggests it is younger than the Oxland travertine. Probably the talus formed before Black Earth Cave became inhabited by large carnivores.

The Channel travertine clearly postdates the canyon in the Norlim travertine and undoubtedly is no older than the Oxland travertine. As noted earlier, the Channel travertine apparently fills a deep notch in the bedrock—a downstream equivalent of the canyon in the Norlim travertine. The individuality of the Channel travertine is difficult to demonstrate because quarry dumps and the coaling station of the quarry railway cover critical areas.

The Channel alluvium overlaps the manganiferous coating on the apron of the Oxland travertine and is, therefore, younger. How much younger is not clear. Also, the alluvium is probably younger than the talus described above. The presence of bog manganese, lack of stratification, and the geographic occurrence of the alluvium suggest a swampy area, possibly a water hole, developed by seepage through the Oxland travertine during the last diversion of the Thabaseek River. The presence of a few crude artifacts of Middle Stone Age under the alluvium, at its contact with the Oxland apron (F. E. P. Loc. 38-7A), and the occurrence of one trimming stone of Late Stone Age in the upper part of the alluvium indicates post-Middle Stone Age.

The occurrence of Middle Stone Age artifacts in fissures in the Norlim travertine and upon the Oxland apron raises rather than solves problems of correlation within the Buxton area. The writer considers the occurrence of Middle Stone Age artifacts in both places suspect. Most of the red earth was deposited before the artifacts were introduced, and conceivably the stone artifacts worked their way down from the surface after all the red earth was deposited. All occurrences of the artifacts in place were isolated and sporadic, and no relation to stratified levels within the red earth could be determined. The unconsolidated, soft, yielding character of the red earth, and continuous decay of the surrounding travertine could allow introduction of extraneous objects such as stone artifacts from the surface following the deposition of the red earth. For purely physical reasons the unconsolidated fills of red earth in the Norlim and Thabaseek travertines seem to fit logically into an arid interval following the formation of the Norlim travertine and before the canyon was cut through it. The few Middle Stone Age artifacts (none is a definitive tool) lying on the Oxland apron and sealed by the Channel alluvium could have been introduced by Late Stone Age peoples known to have inhabited the immediate vicinity. If the Middle Stone Age artifacts were contemporaneous with the upper part of the red earth, then artifacts of the same type occurring on the apron of the Oxland travertine and under the Channel alluvium pose a problem of correlation, for the latter horizon must be much younger than even the upper part of the red earth in the Norlim travertine.

The marked development of a manganiferous

[4] Quarry dumps cover critical areas.

TABLE 1.—OCCURRENCE OF FOSSILS AND ARTIFACTS ALONG KAAP ESCARPMENT

	Faunas											
	Australopithecus Cave: dry phase (lower)	*Australopithecus* Cave: wet phase (upper)	Hrdlicka pipe	Black Earth Cave: lower	Black Earth Cave: upper	Witkrans Cave: lower (M.S.A.)	Witkrans Cave: upper (L.S.A.)	Boetsap	Little Witkrans	Ieor	Powerhouse cave	Ochre cave	Blue Pool Cave
MAMMALIA													
Insectivora													
crocidurines (shrews)	x	..	..	? ←x		..	..	..	..	..	x	x	x
Chiroptera													
microchiropterans (bats, small)	x	..	..	? ←x		..	..	..	..	..	x	..	x
Primates													
Papio (& related baboon genera)	x	x	..	x	x	x	x	..	..	x	..	..	..
Australopithecus	x	→?	..	..	..	..	..	..	..	..	..	..	..
Homo	..	..	..	x*	..	x	..	..	..	..	..	..	..
?*Cercopithecus* (monkey)	..	..	..	..	x	..	..	..	..	..	..	..	..
Lagomorpha—leporid ("hare")	x	..	..	x	..	..	..	..	..	..	x	..	..
Rodentia													
Hystrix (porcupine)	..	..	..	x	x	x	..	..	..	..	x	x	..
small rodents	x	..	..	..	x	x	x	..	..	x	..	x	x
Carnivora													
Lycaon (hunting dog)	..	..	..	x	x	..	..	..	..	..	..	..	..
Thos (jackal)	..	..	..	x	x	x	?	..	..	..	..	..	..
Otocyon (big-eared fox)	..	..	..	x	x	..	..	..	..	..	..	..	..
Vulpes (fox, small)	x	..	..	x	x	..	..	..	..	..	..	..	..
Proteles (aard wolf)	..	..	..	x	..	..	..	..	..	..	..	..	..
hyaenines (hyaenas)	..	..	..	x	x	x	..	..	..	..	..	..	..
lutrines (otter)	..	..	..	..	x	..	..	..	..	..	..	..	..
Mellivora (honey badger)	..	..	..	x	..	..	..	..	..	..	..	..	..
mustelid, small	..	..	..	x	..	..	..	..	..	..	..	..	..
viverrid	..	..	..	x	x	..	..	..	..	..	..	..	..
Panthera (leopard)	..	..	..	x	..	..	..	..	..	..	..	..	..
Leo (lion)	..	..	..	? ←x		..	..	..	..	..	..	..	..
felines, small	x*	..	..	x*	x*	?	x	..	..	..	x	x	..
Tubulidentata													
Orycteropus (aard vark)	..	..	..	x	..	..	..	..	..	..	..	..	..
Hyracoidea													
Procavia (dassie)	x	..	..	x	x	x	x	..	..	..	..	..	x
Perissodactyla													
?*Diceros* (rhinoceros)	..	..	..	x	x	..	..	..	..	..	..	..	..
Equus (small)	..	..	..	x	x	x	x	x	x	x	x	x	..
(intermed.)	..	..	..	x	?	..	..	..	..	..	..	..	..
(large)	..	..	..	x	..	..	..	..	..	..	..	..	..

TABLE 1.—*Continued*

	Faunas													
	dry phase (lower) *Australopithecus* Cave wet phase (upper)		Hrdlicka pipe	lower Black Earth Cave upper		lower (M.S.A.) Witkrans Cave upper (L.S.A.)		Boetsap	Little Witkrans	Iscor	Powerhouse Cave	Ochre Cave	Blue Pool Cave
Artiodactyla														
suines (wart hogs)	..	..	..	x	x	x	x	x	..	..	x	x	..
bovids (small antelope)	x	x	..	x	x	x	..	..	..	x	x	x	x
(large antelope)	..	..	..	x	x	..	..	x	..	..	..	..	..
(buffalo?)	..	..	..	..	x	..	..	?	..	..	x	..	..
AVES														
Struthio (ostrich)	..	..	..	x	→?	..	x	..	..	..	x	..	x
strigid (owl, small)	x	..	..	..	..	..	..	..	..	..	..	..	..
aegypiid (vulture)	..	..	..	x	..	..	..	..	..	..	..	..	..
corvid (raven)	..	..	..	..	x	..	..	..	..	..	..	..	..
anserine (duck)	..	..	..	..	x	..	..	..	..	..	..	..	..
REPTILIA														
Chelonia														
turtle	x*	..	..	x	x	x	..	..	..	..	x	..	..
Squamata														
lacertilian (lizard, small)	x	..	..	..	..	..	x	..	x	..	..	..	..
Varanus (large form)	..	..	..	x	x	x	..	..	..	..	x	..	..
AMPHIBIA														
anuran (toad)	..	..	..	..	..	..	..	..	x	..	x	..	..
OSTEICHTHYES														
teleost	..	..	..	x	..	..	x	..	x	..	x	..	..
INVERTEBRATA														
malacostracan (crab)	x	..	..	..	..	..	..	..	..	..	x	..	..
gastropod (snail)	x	..	x	..	..	..	..	..	..	..	..	..	..
pelecypod (clam)	..	..	..	..	x	..	..	..	..	..	x	..	..
ARTIFACTS	..	..	MSA	?	ash	MSA	LSA	..	..	..	LSA	..	LSA

*More than one species or subspecies.
x→? Position doubtful.

surface zone on the Oxland apron and on the cemented cave deposit at Witkrans suggests contemporaneity and a positive correlation of the Middle Stone Age of Witkrans with the Buxton sequence. However, the manganiferous zone at Witkrans seals in advanced artifacts of Middle Stone Age, whereas cruder artifacts, resembling those of the Norlim fissures occur upon the manganiferous zone of the Oxland travertine. The significance of the artifacts from the Oxland apron, even though sealed by the overlying Channel alluvium, is open to question. Even though the two manganiferous zones may not be exactly contemporaneous as indicated by artifacts, on geologic and physiographic grounds there is no doubt that the Middle Stone Age of Witkrans correlates with the Buxton sequence somewhere between the Norlim and Blue Pool travertines. A critical discovery is that the Witkrans Middle Stone

Age deposit and the fill of black earth at the Hrdlicka site in the Thabaseek travertine contain similar artifacts.

Thus the evidence suggests a period of deposition of black surface zones and black earth between the formation of the Oxland and Blue Pool travertines. The black manganiferous zone on the Oxland apron, on the talus in Norlim canyon, and on the deposit at Witkrans, and the black earth in the Hrdlicka pipe are probably correlatives, or nearly so. Also, except for the uppermost layers, the deposit in Black Earth Cave may be a correlative. The black manganiferous zone is definitely older than Late Stone Age at Witkrans and the Channel alluvium on the Oxland apron; the Hrdlicka pipe contained advanced Middle Stone Age artifacts. A very small, adult human mandible, a bone awl, and a few fragments of ostrich eggshells in upper layers of Black Earth Cave suggest post-Middle Stone Age; physiographic considerations indicate an earlier age for the lower layers. Whereas black earth exists in pipes in the Norlim and Thabaseek travertines, it does not occur within the Oxland travertine apparently because the latter, although older than the period of black-earth deposition, did not have fissures developed at the critical time.

The lack of artifacts of the Old Stone Age in association with the travertines of the Kaap escarpment is puzzling. Painstaking search of the Buxton area, including the extensive dumps and the bordering Harts valley, revealed no artifacts of the Old Stone Age of South Africa. Such artifacts frequently occur in the Younger Gravels of the Vaal River; Wonderwerk Cave, west of Buxton on the Kaap plateau, preserves a remarkable collection of hand axes. Significance, if any, of these facts of distribution may be apparent to archeologists of South Africa, but, at Buxton, the most promising and critical locality producing *Australopithecus*, geologically speaking, there is no positive stratigraphic evidence integrating the Old Stone Age of South Africa with the sequence of travertines.

Correlation of other travertines of the Kaap escarpment with the Buxton sequence is based largely on two fundamental observations: (1) The Boetsap travertine at Fossil Hill is regarded as older than any except possibly the surface breccia of Stage 1 in the Buxton sequence, because the escarpment at Boetsap has receded considerably and there are no fills of red, sandy earth. (2) There is no evidence at Buxton that the escarpment has receded, leaving the oldest travertine perched on outliers or on headlands, as at Boetsap. However, the reconstructed, prequarry surface of the Thabaseek travertine at Buxton clearly indicates a degree of surface dissection not present on the later travertines at Buxton, but not commensurate with the dissection of the Boetsap travertine. Also, the bedrock walls of the old Thabaseek channel, exposed between the Oxland and Norlim travertines, are broadly indented. These features may represent a slight retreat of the escarpment since the deposition of the bordering travertines, but the indentations may also be similar to the indented cliff north of the Blue Pool, a feature resulting from lateral cutting of the Thabaseek River. The travertines at Thoming, Witkrans, and Little Witkrans lack fills of red earth but show evidence of marginal recession not due to stream erosion; therefore they are placed in the interval between the Norlim and the Blue Pool travertines. The artifacts and general history of the Witkrans Cave indicate that the enclosing travertine is at least as old as the Oxland travertine. Lastly, the cyclic nature of the Buxton travertines leads the writer to correlate the travertines at Thoming, Witkrans, and Little Witkrans (and, less certainly, Gaap) exactly with the Oxland travertine, which is clearly intermediate in age between the Norlim and Blue Pool travertines.

Correlation with the Buxton sequence of the Sterkfontein and Makapan cave deposits containing australopithecines is not possible at present. These deposits are in cavities in dolomitic bedrock and are not associated with surface travertines. Here, the geologist will never have the opportunity to study cross sections on so grand a scale as in the Buxton quarries. However, South African workers, for example Robinson (1952), are accumulating geologic data which will greatly facilitate correlations between the Transvaal caves and Buxton. In the Sterkfontein region (5500 ft. el.) the water table in the steeply dipping

dolomite has been low enough, probably since the beginning of the Pleistocene, to allow continuous formation of cave deposits in the dolomitic cavities of the ancient African platform. As detritus sifts and washes downward and eventually becomes cemented, earlier deposits so formed are progressively exposed at the surface. At present, large stalactites occur in place within 15 feet of the surface (*i.e.*, the Mooi River valley west of Krugersdorp). On the Bolt Farm[5] in the Sterkfontein valley the accumulated litter on a cave floor, cemented and containing rotted stalactites, coprolites of hyaenas, and masses of bones and teeth of ungulates, is truncated obliquely by the present surface of a hillside (F. E. P. Loc. 55-16). Also, masses of small bones and teeth from disintegrated owl pellets originally disgorged in a cave occur in cemented cave deposits exposed at the present surface. This indicates that in the vicinity of the Sterkfontein caves the present surface is at least 20-30 feet lower than it was when the cemented, red cave deposits now exposed at the surface were formed. Since all the remains of australopithecines from the Sterkfontein-Kromdraai and Makapan regions are found at or within 25 feet of the surface, it is reasonable to conclude that the man-ape is among the oldest fossils of the cave deposits. However, this physical data does not imply that the age of the australopithecines is Pliocene or even Lower Pleistocene as Broom believed.

Broom (1948, p. 1) regrets the impossibility of dating most of the cave mammals of Taungs, Sterkfontein, and Kromdraai, and takes the geologist to task for not contributing to the problems of correlation. However, Broom, sometimes arbitrarily, assigns the fossil mammals to the Pliocene and Pleistocene. In the writer's opinion, Broom's dating of australopithecines and the associated faunas is an estimate based mainly upon the negative evidence that *Equus* does not occur with australopithecines (Broom and Schepers, 1946, p. 30, 31). Broom (1950, p. 1, 3) reiterates his belief that the cave deposits containing australopithecines may range from the Middle Pliocene to Upper Pleistocene, but points out that his colleagues, Haughton and Cooke, believe these same deposits are contemporaneous. Broom and Robinson (1949) describe a new primate, *Telanthropus*, intermediate between australopithecines and modern man (euhominid) from the Swartkrans locality. The same authors (1950, p. 153) conclude that at Swartkrans *Telanthropus* and *Paranthropus* are contemporaneous. Robinson (1952) describes in detail the Swartkrans deposits, and (1953) the morphology and taxonomy of *Telanthropus*. Of particular interest to the present discussion, Robinson (1953, p. 449) states that the australopithecine localities, while not exactly the same age, are generally similar in age; that (p. 450) *Equus* occurs at Swartkrans with *Paranthropus*; and that (p. 451) the Swartkrans deposit does not indicate arid conditions as has been generally assumed for all australopithecine deposits.

As now known, the nature of the occurrences of australopithecines demands a revision upward of their stratigraphic position. It seems highly improbable that upon the elevated African platform a vigorous erosion (such as surely has taken place) would consistently allow cave deposits of Pliocene or even early Pleistocene age to persist to the present time in the Sterkfontein, Kromdraai, Makapan, and Kaap regions. Certainly in North America, where there have been favorable conditions for persistence of old cave deposits, the known cave faunas of Quaternary age are Middle Pleistocene or later. Also South African archeological and faunal facies may very well lag behind European equivalents in point of time and hence be actually much younger than Broom believes. A somewhat similar occurrence of older forms in a peripheral region is found in the late Pleistocene of Florida where a number of extinct genera—*Megalonyx*, *Paramylodon*, *Mammut* and the North American *Equus*—are associated with *Homo sapiens* (Gazin, 1950, p. 398). Species of *Equus* are found with australopithecines at Swartkrans, and they occur in cave deposits now exposed at the surface on the Bolt Farm neighboring Swartkrans and Sterkfontein. Also, *Equus*

[5] The University of California party mapped more than 20 fossiliferous cave deposits, all at or near the surface, on the Bolt Farm, which is immediately upstream from the Swartkrans locality, site of giant australopithecines.

occurs in the Boetsap fauna which on physical data appears to be somewhat older than the *Australopithecus* fauna. Where horse remains appear in the Kaap and Transvaal cave deposits, they were transported there by carnivores, particularly hyaenas. Probably the man-ape did not prey on horses (or other large ungulates), and the haunt of the man-ape was not that of the scavenging hyaena. On this point Broom (1946, p. 31) notes that *Australopithecus* Cave contains nothing indicative of the presence of large carnivores. Thus, a facies difference mainly peculiar to cave deposits may account for the frequent lack of horses in association with australopithecines, whereas the geologic occurrence of both forms suggests a general contemporaneity. If contemporaneous with *Equus* and euhominids, the australopithecines certainly do not antedate the Pleistocene; and, if the principle of "lag" faunas in South Africa is valid, the australopithecines may be no older than the Middle Pleistocene. The soundness of this line of reasoning seems to be borne out by the place of *Australopithecus africanus* in the Buxton sequence of events.

Concerning the age of the australopithecine fauna, Cooke (1952, p. 61) states,

> "... The evidence favours a broad correlation of the ape-man fauna with the Lower Quaternary stage known as the Villafranchian. The late Dr. Broom contended for a long time that the deposits were Pliocene, but in his later work conceded that part may be Lower Pleistocene (Quaternary) in age. I feel he placed undue weight on the occurrence in the ape-man deposits of animals very similar to Pliocene types occurring in Europe and Asia, and also that he exaggerated the length of the ape-man period. Most of our assemblages of fossil mammals from South Africa are strange mixtures of 'recent-looking' species and archaic forms, so it seems that this southern tip of the African continent was in the nature of a cul-de-sac in which archaic forms survived, long after they had become extinct in the more rigorous and variable climate of C uaternary Europe."

Correlation of the Buxton sequence with the Vaal gravels raises problems, for, on the one hand, the sequence of the gravels and gravel terraces is not yet clearly understood; and, on the other hand, opinions differ on the climatic interpretation given to bodies of travertine. Zeuner (1945, p. 20) states flatly that travertines (originating from cold springs) require a fairly constant water supply and, therefore, a humid climate. Both Branner (1911, p. 190) and Young (1925, p. 65), who studied the Catinga travertines of Brazil and the Kaap travertines of Africa, respectively, concluded that the cliff-forming travertines (carapace lime) were formed during relatively dry periods. Evidently Branner and Young's statements were based primarily on the field observation that the travertines block pre-existing stream channels. Certainly in the Buxton area vigorous channel erosion by water follows the formation of the Norlim travertine, precedes and follows the formation of the Oxland travertine, and precedes the formation of the Blue Pool travertine. This does not necessarily mean that the travertines represent the period of maximum aridity; rather, it seems likely that the travertines represent either the onset of aridity (or the waning stage of a relatively humid period) or the onset of a humid period (or the waning of an arid period). However, the apron lime underlying the carapace lime of the Thoming and Oxland travertines exhibits clear evidence of flowing water in the lenses of sandy detritus—an indication that water was more plentiful earlier than later in the genesis of these travertines. Also, the black manganiferous zone on the surface of the apron of the Oxland travertine suggests decreasing humidity following the formation of the travertine. The fossil plants in the Thoming travertine indicate that the floral assemblage living in the area during the building of the travertine is generally similar to the semiarid assemblage now living in the area, except for two species now living in a somewhat more humid climate to the north. Therefore, it seems that the travertines of Buxton cannot represent the peak period of humidity, for the periods of vigorous cutting belong here; and, on geochemical grounds, it is unlikely that the travertines represent periods of excessive aridity.

In any event, it seems highly significant that there are two large, older travertines and two smaller, younger travertines at Buxton; and there are two large, older pluvials and two smaller, younger pluvials interpreted from the Vaal River valley by Cooke (1947, p. 511). The correspondence is even closer when the

relative ages of the different travertines, the relative ages of the pluvials, and the associated archeological evidence are considered.

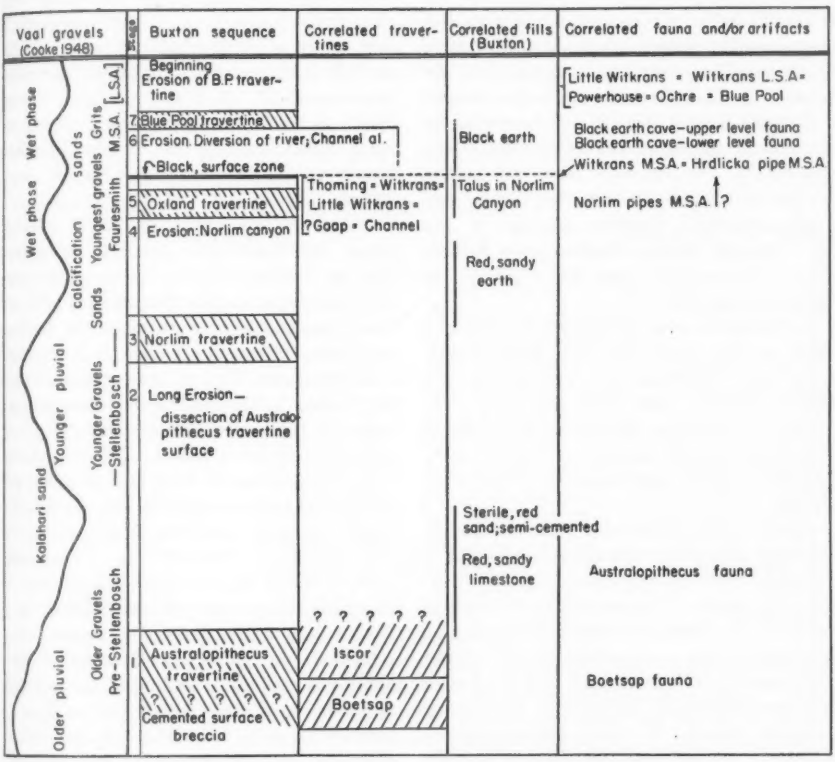

FIGURE 12.—CORRELATION OF TRAVERTINES AND ASSOCIATED PHENOMENA ALONG KAAP ESCARPMENT

With diamond gravels and associated phenomena along Vaal River

Cooke (1947, p. 509) still is in essential agreement with current views (as of 1952) of Van Riet Lowe, who has graciously allowed the writer to see, and quote from, the correlation chart in his most recent manuscript on the Vaal river entitled, *The Vaal River chronology: an up to date summary*. With this information available, the writer presents (Fig. 12) his opinions on the correlation of the Buxton sequence of events. It seems worth while to do this in a preliminary report because the geologic events clearly represented at Buxton may be a useful standard for the Quaternary of South Africa. Here is a relative "chronology founded on geology irrespective of archaeological considerations" which Zeuner (1945, p. 212) thinks is necessary to work out Pleistocene chronology properly. But the Buxton sequence has the added advantage of associated archeological as well as fossil remains. Probably Zeuner (1945, p. 220) was correct in his assertion that the Union of South Africa is more promising than any other country outside Europe for working out Pleistocene chronology.

SUMMARY

In 1947 and 1948 the paleontological party of the University of California South African

Expedition investigated the travertines and associated deposits along the Kaap escarpment from Gaap to Vryburg, Cape Province. A travertine mass typically developed on the dolomitic cliff of the escarpment consists of a carapace of irregularly hemispherical layers of nearly pure lime overriding an apron of rubbly, impure lime. Individual travertine formed during the waning stage of one or another of the several successive pluvial periods of the Quaternary. The numerous caves and fissures in the travertines contain fossiliferous and implementiferous deposits ranging in age from at least Middle Pleistocene to Recent; the travertines may span the whole of the Quaternary period.

At Buxton in the Taungs Native Reserve, there are two major and two minor travertines—the Thabaseek and Norlim, and the Oxland and Blue Pool. Each is related to the others, to contained fissure deposits, and to water-cut channels in such a manner as to represent a seven-stage sequence of events as follows:

STAGE 1: The Thabaseek River at Buxton originally flowed over the Kaap escarpment in a channel trending southeast probably following joint planes. Cementation of the surface rubble in the channel preceded the formation of a large body of travertine mostly on the southwest side of the channel. This Thabaseek travertine eventually blocked the channel and probably shunted it northeastward slightly.

STAGE 2: A long period of erosion sculptured the surface of the Thabaseek travertine and truncated certain of its fissure deposits. Early in this stage a cave system near the eastern periphery of the travertine accumulated fossil vertebrates including *Australopithecus africanus* Dart. The cave contained deposits indicating a change from dry to wet conditions. The type skull of *Australopithecus* may have come from the later wet phase rather than from the earlier dry phase as heretofore believed.

The Thabaseek travertine in the vicinity of the *Australopithecus* Cave contained three generations of cave or fissure deposits; the earliest deposit contained *Australopithecus*; only the latest deposit has an equivalent in deposits in the younger travertines of Buxton.

STAGE 3: Another large body of lime, the Norlim travertine, built out from the northeast side of the Thabaseek channel, completely blocking it, and overlapped part of the Thabaseek travertine. The travertines were extensively fissured, and large amounts of red, sandy earth accumulated in the Norlim as well as in the older Thabaseek travertine. Artifacts of the Middle Stone Age of South Africa occur in the upper levels of the red earth indicating that the Norlim travertine antedates the Middle Stone Age of South Africa.

STAGE 4: The Thabaseek River re-established its pre-Norlim channel by cutting through the Norlim travertine down into bedrock, leaving a sharply incised canyon in the travertine and a deep notch in the bedrock escarpment below the canyon. A cave system with entrance(s) high in the northeast wall of the canyon in the Norlim was truncated and began to receive deposits of earth.

STAGE 5: A small body of lime, the Oxland travertine, built out from the northeast side of the Thabaseek channel several hundred yards upstream from the Norlim travertine, and completely blocked the channel once more. Waning of stream erosion allowed an extensive talus to accumulate at the base of the canyon walls. The talus became semicemented, and its surface developed a manganiferous zone sometime before stage 6. The apron of the Oxland travertine developed a similar manganiferous zone on the talus—probably contemporaneously and indicating increasing dryness. Possibly at this time the channel below the canyon in the Norlim travertine was filled with the Channel travertine.

STAGE 6: In an effort to re-establish its channel, the Thabaseek River cut through the bedrock above the Oxland travertine and curved around the north side of the Norlim travertine. Then the river transected the Norlim apron and rejoined the old channel. In the diversion, the upstream portion of the Oxland travertine was truncated and removed. Seepage created a swampy area below the dam of Oxland travertine, and here, overlapping the Oxland apron, accumulated the thick Channel alluvium. At this time bones and teeth of vertebrates, mostly mammals and including *Homo*, accumulated in the Black

Earth Cave high in the northeast wall of the canyon in the Norlim travertine.

STAGE 7: A small body of lime, the Blue Pool travertine, accumulated in the youngest Thabaseek channel where it truncates the Oxland travertine and plunges over the dolomite cliff. The Blue Pool travertine is being eroded marginally, and the Thabaseek river is shifting northward against bedrock. Transection of the Norlim apron in Stage 6 exposed Powerhouse Cave, which in Stage 7 accumulated a Wilton culture of the Late Stone Age.

Other travertines along the Kaap escarpment from Gaap to Vryburg have no cave deposits comparable to those at Buxton. At Boetsap, a cave deposit containing fossil ungulates, including *Equus*, probably antedates the *Australopithecus* fauna. At Witkrans, a cave deposit yielded artifacts of the Middle Stone Age associated with numerous remains of vertebrates, including *Homo*, and a sparse Wilton culture of Late Stone Age. At Little Witkrans a shelter deposit contains artifacts of the Wilton culture and associated vertebrates.

Correlation of main events within the Buxton sequence is clear, but outside the area correlations are only tentative. The Boetsap travertine is considered older than the Thabaseek travertine because of the greater degree of erosion; the cave deposit at Boetsap antedates the period of erosion affecting the travertine. The Iscor travertine had many cave deposits resembling the deposit of *Australopithecus* Cave, but quarrying has removed all fossiliferous deposits. Travertines at Thoming, Witkrans, Little Witkrans, and Gaap correlate best with the Oxland travertine because they all lack fills of red, sandy earth such as occur in the older travertines at Buxton and each shows definite signs of peripheral recession. The Middle Stone Age deposit in the Witkrans travertine provides archeological evidence which aids in correlating this travertine with the Oxland travertine.

In the Buxton area, periods of vigorous channel cutting followed closely by deposition of channel-blocking travertine seem to correspond to the degradational phase of the pluvial-interpluvial cycles of the African Quaternary. The two older, major travertines and the two younger, minor travertines at Buxton correlate well with the waning stages of the two older, major pluvials and the two younger, minor pluvials interpreted from the Vaal gravels and terraces by Cooke.

On the basis of geological, physiographic, and archeological data the age of the Taungs man-ape, *Australopithecus africanus* Dart, appears to be no older than Lower Pleistocene, and possibly is Middle Pleistocene.

REFERENCES CITED

Branner, J. C., 1911, Aggraded limestone plains of the interior of Bahia and the climatic changes suggested by them: Geol. Soc. America Bull., v. 22, p. 187–206, 2 figs., 4 pls.

Broom, Robert, 1948, Some South African Pliocene and Pleistocene mammals: Transvaal Mus. Annals, v. 21, p. 1–30.

—— 1950, The genera and species of the South African fossil ape-men: Am. Jour. Phys. Anthropology (new ser.), v. 8, no. 1, p. 1–13, 5 figs.

Broom, R., and Robinson, J. T., 1949, A new type of fossil man: Nature, v. 164, p. 322, 2 figs.

—— 1950, Man contemporaneous with the Swartkrans ape-man: Am. Jour. Phys. Anthropology (new ser.), v. 8, p. 151–155, 6 figs.

Broom, R., and Schepers, G. W. H., 1946, The South African fossil ape-men, the Australopithecinae: Transvaal Mus. Mem., no. 2, p. 1–272, 57 figs., 18 pls.

Camp, C. L., 1948, University of California African Expedition—Southern Section: Science, v. 108, p. 550–552.

Cooke, H. B. S., 1947, Variation in the molars of the living African elephant and a critical revision of the fossil Proboscidea of Southern Africa: Am. Jour. Sci., v. 245, p. 434–517, 14 figs.

—— 1952, Mammals, Ape-men and Stone Age men in Southern Africa: South African Archaeol. Bull., v. 7, p. 59–69, 3 pls.

Gazin, C. L., 1950, Annotated list of fossil Mammalia associated with human remains at Melbourne, Fla.: Washington Acad. Sci. Jour., v. 40, p. 397–404.

Robinson, J. T., 1952, The Australopithecine-bearing deposits of the Sterkfontein area: Transvaal Mus. Ann., v. 22, p. 1–19, 5 figs., 3 pls.

—— 1953, *Telanthropus* and its phylogenetic significance: Am. Jour. Phys. Anthropology (new ser.), v. 11, p. 445–501, 14 figs.

Young, R. B., 1925, The calcareous tufa deposits of the Campbell Rand, from Boetsap to Taungs Native Reserve: Geol. Soc. South Africa Trans., v. 28, p. 55–67, 3 figs., 3 pls.

Zeuner, F. E., 1945, The Pleistocene period, its climate, chronology and faunal successions: London, Ray Society, p. xii + 322, 76 figs.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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Short Notes

INFLUENCE OF CYCLIC PROCESSES ON THE EVOLUTION OF THE EARTH'S CRUST

BY SIDNEY PAIGE

Of three Bownocker lectures delivered at The Ohio State University March 3 and 4, 1952, one was entitled *The Influence of Cyclic Processes on the Evolution of the Earth's Crust.* An abstract of the main thesis of that paper follows.

The energy of solar radiation, that of chemical transformations, that residing in the gravitational field of the earth, and other forces, working through the atmosphere and hydrosphere upon a primitive basaltic outer surface of the earth have transformed it through billions of years to one of striking density differences—the largely sialic sedimentary continents, on the one hand, balanced against the simatic, igneous ocean basins on the other hand. Thereby forces are supplied which, with others, are responsible for the continued growth of continental segments, their evolution and their deformation.

Basaltic rock of the primitive crust was, and basalt today is unstable under the physical and chemical transformations arising at the discontinuity of a solid crust with an enveloping gaseous atmosphere. These changes stem from the hydrologic cycle of weathering, transport and sorting, chemical diffusion in solution, subsequent deposition of sediments, their subsidence, burial, deformation, and metamorphism.

These processes have led in the main to progressive chemical transformations and density changes toward the sialic and lighter sedimentary rocks of the continental segments as opposed to the simatic and heavier igneous rocks of the ocean basins. The process of conversion calls for a continued supply of simatic rock, which has been abundantly available through invasion and extrusion throughout the observable record of geologic time.

The principle of isostasy is fundamental to the operation of the entire repetitive hydrologic cycle and with it supplies some but not all of the forces that acting through density differences in the outer crust develop geosynclines, deform them, and bring about striking chemical and physical changes—the development of sedimentary crystalline schists and gneisses, and ultimately through ultrametamorphism the diorite-granite suite of plutonic rocks.

Isostatic adjustment calls for the flow of plastic simatic rock from depths beneath the ocean floors toward and under the rising continental segments, unloaded by erosion.

Such movements could result in the formation of drag folds on the ocean floor and thus be partly responsible for island arcs and their accompanying deeps and be partly responsible for linear geosynclines along continental borders.

Rising continental segments subject to erosion and under-running by simatic rock would seem to be inevitably subjected to tensional stresses, to spreading and creep toward the ocean basins, and would thus develop components of gravitational stress toward the basins.

The movement of simatic material toward the high-standing continents opposed by the higher-level stresses arising in the creep toward the basins would seem to have given rise to widespread underthrusting sustained partly by gravitational forces. These dislocations could play an important role in the formation of island arcs and the initiation of volcanism.

With volcanism established the hydrologic

cycle begins anew. The island arcs are thus finally captured by the continental segments from which apparently many of them spring if one may judge by the fringing Asiatic arcs. Thus the continental segments grow and encroach upon the ocean basins. The development of successively intercepting Asiatic island arcs suggests itself as an example of these forces in operation.

The processes outlined above seem to explain the concentration of most of the useful metals and fuels, the connection of so many ore deposits with the diorite-granite suite of intrusives, the concentration of radiogenic activity within the sialic rocks and within sediments, and also to corroborate the thesis of Gilluly that deformation of the crust is essentially continuous in time but not in space.

The writer is now engaged in a further examination of the sources of energy involved in the evolution of the earth's crust. On the basis of the foregoing concepts and recent work he suggests at this time that with respect to the evolution of the earth's crust two great discontinuities are outstanding—one at the base of the atmosphere, and the other known as the Mohorovičić discontinuity, some 35 km beneath the surface of the continents, some 10 km beneath the surface of the ocean waters.

These discontinuities, together with the energy of the sun's radiation and hydrologic cycle, and such forces as those involved in the gravitational field of the earth, in the residual heat of the earth, in the relationships of the temperature pressure gradients to the melting points of rock, in the density distribution within the earth, and in the figure of the earth—all these forces when correctly integrated should lead to a logical unifying principle controlling the evolution of the earth's crust, which is after all but a minute shell of the vast interior.

This Note is an eclectic synthesis of many ideas and observations by many workers in many fields on many continents during the past hundred years. It is therefore impossible to give credit to all to whom I am indebted, but the works of James Gilluly, Beno Gutenberg and his collaborators, Marshall Kay, H. H. Read, John L. Rich, J. Tuzo Wilson, and particularly the inspiring paper by Andrew C. Lawson deserve citation. The work of Harry Hess and David Griggs has also influenced the writer.

References Cited

Gilluly, James, 1949, Distribution of mountain building in geologic time: Geol. Soc. America Bull., v. 60, p. 561–590.

Gutenberg, Beno, *Editor*, 1953, Internal constitution of the earth: New York, Dover Publications Inc., 439 p.

Kay, Marshall, 1951, North American geosynclines: Geol. Soc. America Mem. 48, 143 p.

Lawson, Andrew C., 1932, Insular arcs, foredeeps, and geosynclinal seas of the Asiatic coast: Geol. Soc. America Bull., v. 43, p. 353–381.

Read, H. H., 1948, Granites and granites, *in* Gilluly, James, *Chairman*, Origin of granite, p. 1–20: Geol. Soc. America Mem. 28.

Rich, John L., 1951, Origin of compressional mountains and associated phenomena: Geol. Soc. America Bull., v. 62, p. 1179–1222.

Wilson, John Tuzo, 1949, The origin of continents and Precambrian history: Royal Soc. Canada Trans., 3d ser. v. 43, sec. 4, p. 157–184.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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BATHYMETRIC CHART OF THE ARCTIC OCEAN ALONG THE ROUTE OF T-3, APRIL 1952 TO OCTOBER 1953

By A. P. Crary

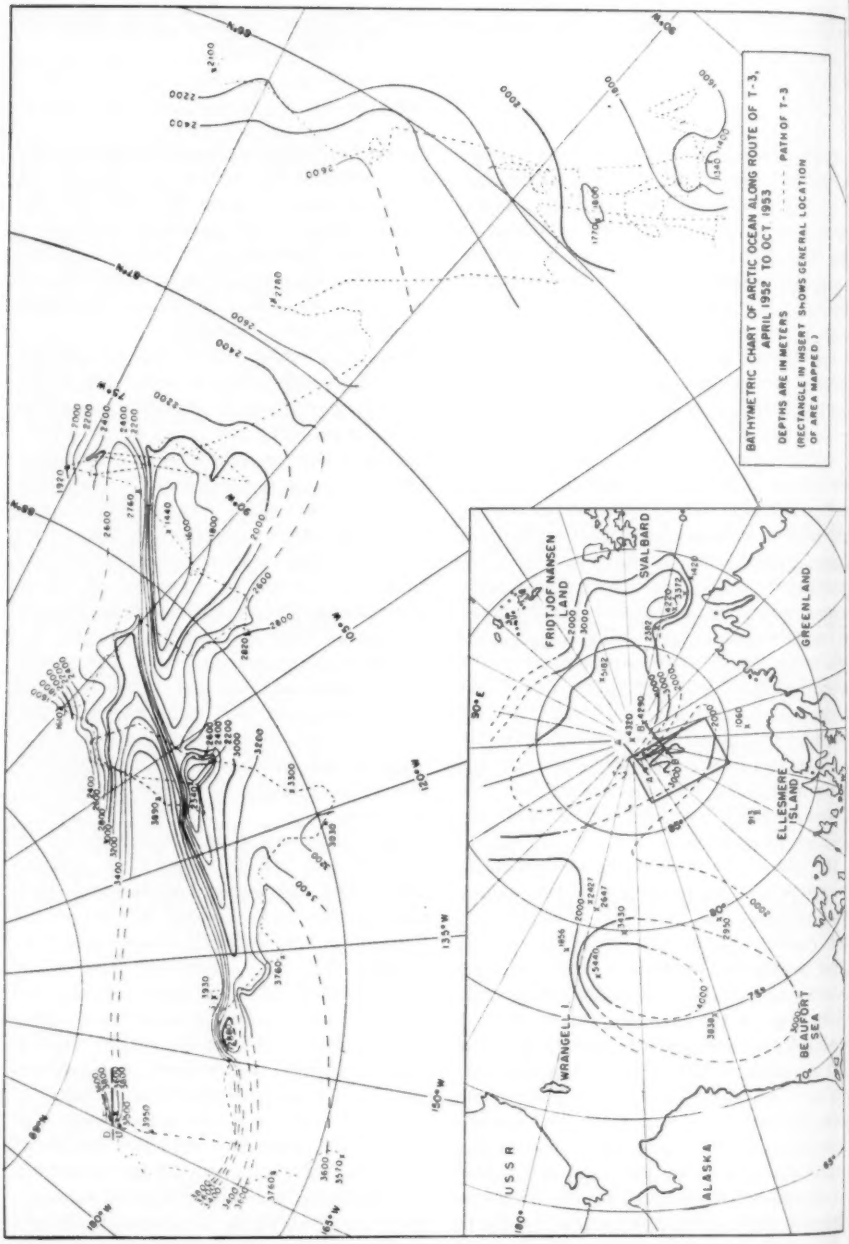
During United States Air Force operations on Fletcher's Ice Island, commonly known as T-3 (Crary, Cotell, and Sexton, 1952), an opportunity was presented for the collection of data on Arctic Ocean depths and for certain geophysical studies pertaining to the strata underlying the ocean. Included in the latter category are gravitation, refraction, and reflection data. This report briefly presents the bathymetric data. A later more comprehensive report will cover details of the bathymetry as well as the results of the geophysical studies.

To study the character of the ice island, a wide variety of portable seismic equipment was used, including a standard seismic prospecting unit, with geophones and amplifiers from the Century Geophysical Corporation, and a 12-galvanometer oscillograph of the Heiland Research Corporation. Except for a few instances, all depths were obtained with this equipment while using electric detonators as the source of acoustic energy. In the 18-month period, 218 depth determinations were obtained. During this time the island moved about 1500 km in an erratic course generally southeast, the total path ranging between the 85th and 89th parallels of latitude and between the 75th and 165th west meridians.

The island, averaging about 165 feet thick, was a poor platform for the sonic depth studies. Efficient explosions could be obtained only with considerable trouble, and the varying island thicknesses would have made dip studies unreliable. Hence, all operations were made off the edge of the island on the ice pack. A two-directional array of four to eight detectors with distances of 120 to 600 meters on a side was used for about 75 per cent of the depth shots; the remainder were made with a single detector. During December 1953, an open lead formed immediately off the island and carried the equipment more than a mile off shore. Until this was located and reset, a few depths were obtained with a Brush Development Company pen and ink recorder. During March 1953 pack-ice pressure against the island caused some damage to the oscillograph. Although an array was again set up in May 1953, the dip results thereafter were unreliable except on a few records. Fortunately, the drift of the island during this latter period was such that the area was eventually well covered and the depth changes were relatively small.

The island locations were obtained from sun or star lines about twice a week. Most of the locations are believed to be accurate to within about a mile, and many to within half a mile. The depth shots were located by interpolation between the astronomical fixes. In some cases of erratic island drift over rapidly changing depths, the observed depths and dips do not conform. In these cases more weight was given to the dip information, since the directional control was at all times sufficiently accurate for the purpose. The dip values are especially important in mapping the northern and western areas. Because the movement of the island could in no way be controlled, many interesting features could be only partially examined, but in places of high dip these data were of great assistance in obtaining the correct strike of the ocean bottom.

The depths were determined by finding the corrected time to 0.001 second of the reflected sound wave, then computing the water depth using the velocity determined by the formulae $V(m/sec) = 1442 + 6.8\,T$ for total travel time, T, more than 3.5 seconds, and $V(m/sec) = 1443 + 6.7\,T$ for travel times less than 3.5 seconds. These formulae agree with figures given by Kuwahara (1939) for the velocity dependence on salinity, temperature, and pressure, and the information available on the temperatures and salinities in the Arctic Ocean. The dips of the ocean floor were also calculated, using the above velocities, on the assumption of straight-line travel paths. Account was taken of the dips in obtaining the vertical depths used in the contouring. The timing reed of the oscillograph was checked regularly with a special


BATHYMETRIC CHART OF ARCTIC OCEAN ALONG ROUTE OF T-3, APRIL 1952 TO OCT 1953
DEPTHS ARE IN METERS
(RECTANGLE IN INSERT SHOWS GENERAL LOCATION OF AREA MAPPED)
PATH OF T-3
FRIDTJOF NANSEN LAND
SVALBARD
GREENLAND
ELLESMERE ISLAND
WRANGELL I.
BEAUFORT SEA
USSR
ALASKA
90° E
135° W
180° W
180°
65°
70°
75°
80°
85°

10-second break-circuit chronometer which was the timepiece for the astronomical observations of position. This instrument had a rate well known from radio checks with WWV time signals.

Along the northern edge of this basin the rise is not so abrupt, except in the far northwestern corner. A limited stay here precluded any detailed mapping, but the dips were 5° to 16° and generally southerly. The recurrence of increased depths running northward has been interpreted as faulting. The correlation of this rise with that noted farther east is questionable. The latter is more uniform, and the dips are gentler. A high figure of 1610 meters was obtained here, but dips are still fairly steep (6°–8° SW.). The deep polar basin near the North Pole lies farther along on this same trend. The intervening ridge may well rise to within 1000 meters or less of sea level.

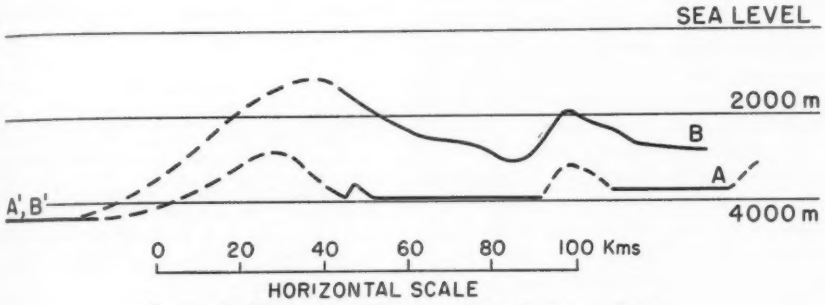


FIGURE 2.—BATHYMETRIC SECTIONS ACROSS SURVEYED AREA
See Figure 1 for location of sections.

Figure 1 shows the results of the bathymetric work. The depths are relatively shallow, considering the data obtained from previous work in the central Arctic basin during drifts of the FRAM (Nansen, 1904), SEDOV (Badigin, 1940), and the NORTH POLE party (Papanin, 1947). Depths along the T-3 route nowhere exceeded 3950 meters, while the minimum depth obtained was 1340 meters.

The most striking feature is a steep rise of 500 to 1500 meters running east and west across the mapped area. This scarp was crossed several times, showing in several places dips of 10°–23°, although the depth change usually occurred between consecutive depth shots without indication of dip. During the first month of operation in the western part of the outlined area, and before all scientific equipment had been delivered, only a few depths were obtained, and these without dip control. The possible extension of the scarp in this area is shown in dashed lines and is located on the evidence of the gravity-meter readings. These were obtained daily during this period and later showed good correlation with water depths when both types of data were available.

North of the scarp and in the western part is an extremely flat basin dipping at most 1 part in 1000. At about 105°W. longitude, this valley narrows into the mouth of a canyon which rises about 1500 meters in 120 kilometers toward the eastern part of the area.

South of the main scarp the elevations fall off less abruptly into another valley, again extremely flat on the western side and rising finally toward the east where it is only partially mapped but appears to turn southeast. Still farther south, a rise out of this basin is indicated along the western side by a single depth with no dip control, and farther east by a high point near 120°W. Long. and 88°N., Lat. where the track of the island turned north.

Through the eastern areas, where the water depths are all less than 3000 meters, runs a broad, east-west trough with a low of 2780 meters. This trough appears to branch out toward the west around the indicated high points near 88° N. Lat. In the southeastern areas are two small, conical mounds of 100 to 200 meters of closure in the gradual rise south of the broad trough. The southern mound has a minimum depth of 1340 meters and is still undefined toward the south.

On 3 May 1952, a plane landed at the geo-

graphical North Pole when the island was only 75 nautical miles from the pole. A sounding was made here of 4320 meters, comparing closely with the depth of 4290 meters obtained during the Russian NORTH POLE drift at 88°54′N. and 20°W.

The relation of the depths mapped from T-3 with others in the central Arctic basin are illustrated in the insert of Figure 1. Cross sections (Fig. 2) show the ridge and valley system in this area. The abrupt change to the flat basins on the western cross section (A) is well determined by the dip analysis. The flat basins vary considerably in depth. Profile BB′ of Figure 2 has the general appearance of submarine canyons. The basins to the west are probably formed individually by the gradual filling of these canyons.

The results of the depths mapped suggest that the Arctic Ocean deep basin is perhaps limited to two areas north of Siberia and northwest of Alaska. Recent depths obtained in the area north of Alaska by Worthington (1953) and Crary, Cotell, and Oliver (1952) would alter somewhat the depth mapping by Emery (1949). The postulation of a generally shallow Arctic area with two separate basins appears more probable than that of a narrow submarine ridge. More detailed mapping must await further soundings. These should be forthcoming soon if the route of T-3 passes into the central Arctic Ocean area.

ACKNOWLEDGMENTS

Acknowledgments are due R. D. Cotell, T. S. Sexton, and R. R. Shorey for their assistance in operation of field equipment at various intervals during the period and to N. Goldstein for assistance in the preparation of the final map.

REFERENCES

Badigin, K. S., 1940, On the Ship GEORGII SEDOV across the Arctic Ocean: Book I, Moscow, Izd. Glavsevmorputi, p. 432–434, 547–553.

Crary, A. P., Cotell, R. D., and Oliver, Jack, 1952, Geophysical studies in the Beaufort Sea: Am. Geophys. Union, Trans., v. 33, p. 211–216.

Crary, A. P., Cotell, R. D. and Sexton, T. F., 1952, Preliminary report on scientific work on Fletcher's Ice Island, T-3: Arctic, v. 5 no. 4, p. 211–223.

Emery, K. O., 1949, Topography and sediments in the Arctic Basin: Jour. Geology, v. 57, p. 512–521.

Kuwahara, S., 1939, Velocity of sound in sea water and calculations of the velocity for use in sonic soundings: Hydrog. Rev., v. 16, p. 123–140.

Nansen, F., 1904, The Norwegian North Polar Expedition, 1893–96: Longmans, Green and Co., London, v. IV, no. 13, p. 1–232.

Papanin, Ivan, 1947, Life on an Ice Floe: London, Hutchinson and Co., 240 pages.

Worthington, L. V., 1953, Oceanographic results of Project Skijump I and Skijump II in the Polar Sea, 1951–52: Am. Geophys. Union Trans., v. 34, p. 543–551.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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ROTATING STAGE FOR PROJECTING ROCK THIN SECTIONS IN POLARIZED LIGHT

BY SAM ROSENBLUM

This note gives a brief description of a rotating stage for projecting 1 by 2 inch or 2 by 2 inch thin sections of rocks in a 3 by 4 inch slide projector. This device enables a large audience to view the image of a thin section that can be rotated between crossed polaroid filters, similar to the image seen through a petrographic microscope. The advantages of projecting such an image in a classroom or at a scientific meeting are self-evident. In fact, two working models fastened together were used successfully at the 1953 meeting of the Rocky Mountain Section of The Geological Society of America in Butte, Montana.

The stage may be made from ⅛-inch flat metal stock, thin sheet metal, a 2 by 2 inch glass slide, two thin polaroid filters, a small knurled pulley, radio cable and spring, wire, flat spring steel, and assorted small screws. The total cost of materials for building one brass and one aluminum stage was about $20. These stages were constructed by the writer in about 8 hours; little intricate machining was involved.

Figure 1 shows the details of the stage, with a perspective view for clarity. The body of the stage is made from ⅛ by 4 inch brass or aluminum for strength and durability. A narrow shoulder is bored into one side of the body around the large hole to receive the rotating disc, and top and bottom strips are fastened with several small screws transforming the body into a broad U-beam. Both top and bottom strips should have thin slots where the "analyzer" polaroid may be slid easily into or out of the optical system. The dimensions of the stage body can be altered to fit any individual projector.

The rotating disc consists of two rings fastened together by flathead screws that also hold the glass stage and two spring clips in place. Since the sketches were drawn, it has been suggested that the disc may be made from one piece of metal. Also, only one wide spring clip, which may be cut out of a metal erasing shield, can be used to allow slides to be inserted more easily. The V-shaped groove in the periphery of the disc is for the radio cable and should allow the small spring to travel completely around it when driven by the pulley from outside the projector. The deeper rectangular groove is merely clearance for the thin retaining strips. The bearing surfaces should be held to a minimum; and graphite powder will further reduce friction.

If two stages are fastened end to end by means of a flat metal strap, then one of the knurled pulley knobs should be less than the thickness of the stage to allow it to be inserted into the projector; the other one may be longer to allow more ease in operating.

Thin plastic polaroid filters are fastened to the back of the stage body and to the sliding thin sheet-metal holder. With the vibration directions of the polaroids crossed, the field is very deep blue to black. Because the filter buckles and discolors with excessive heat, the use of high-wattage lamps—such as 1000-watt lamps—should be avoided. Satisfactory results are obtained by using a 500-watt lamp with adequate ventilation and alternate use of two stages fastened together.

Inserting standard 1 by 2 inch or 2 by 2 inch thin sections in the present equipment, as illustrated, merely involves placing the slide on the surface of the glass stage with the length parallel to the stage clips, and rotating it 90° clockwise, thereby sliding the ends of the thin section under the clips. To remove, simply continue the clockwise rotation until the slide is free and lift it out—a matter of a few seconds of handling.

Undoubtedly, as the stage is used more, suggestions for improving the design and workability of the models will come up, even as they have since the sketches were drawn. Many thanks are due the writer's coworkers for the suggestions offered thus far; and special

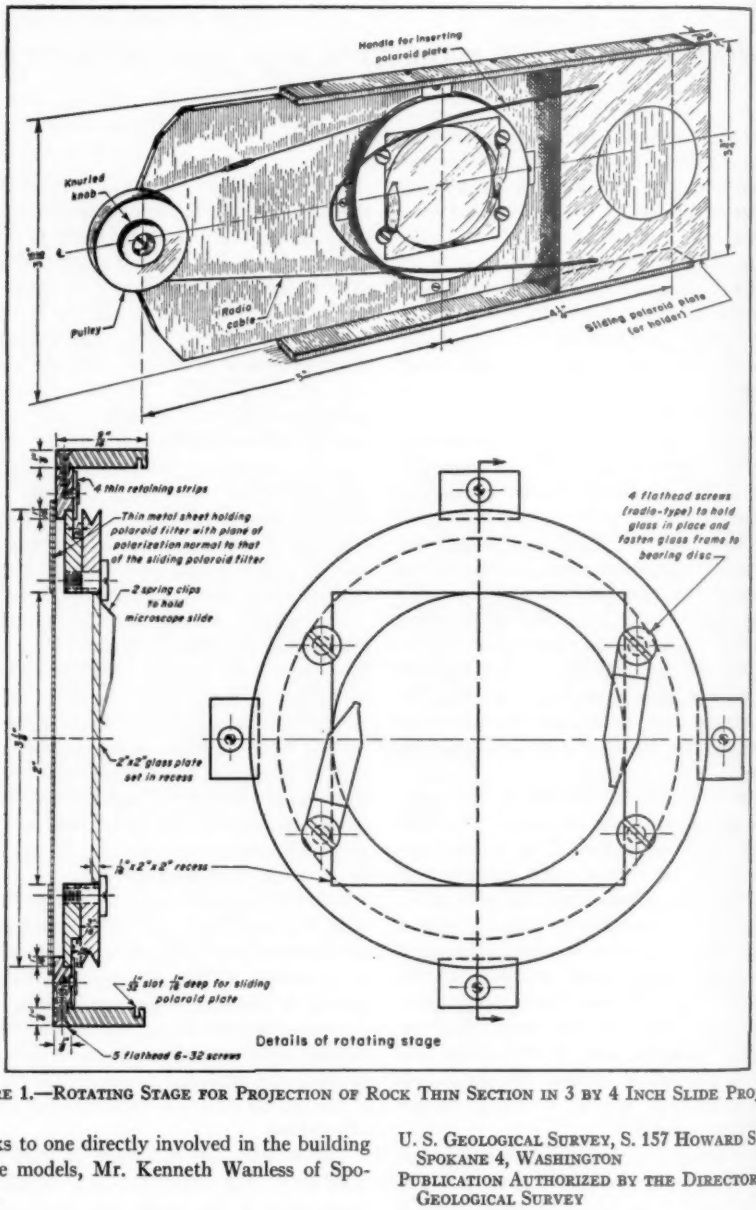
Handle for inserting polaroid plate
Knurled knob
Pulley
Radio cable
Sliding polaroid plate (or holder)
4 thin retaining strips
Thin metal sheet holding polaroid filter with plane of polarization normal to that of the sliding polaroid filter
2 spring clips to hold microscope slide
2"x2" glass plate set in recess
1/16"x2"x2" recess
1/32" slot 1/16" deep for sliding polaroid plate
5 flathead 6-32 screws
4 flathead screws (radio-type) to hold glass in place and fasten glass frame to bearing disc
Details of rotating stage

FIGURE 1.—ROTATING STAGE FOR PROJECTION OF ROCK THIN SECTION IN 3 BY 4 INCH SLIDE PROJECTOR

thanks to one directly involved in the building of the models, Mr. Kenneth Wanless of Spokane.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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VOLCANISM AND AEOLIAN DEPOSITION ON MARS

By Dean B. McLaughlin

The writer has recently developed a hypothesis to account for some of the surface features of Mars in terms of known geological and meteorological processes. Details will be published in one of the astronomical journals, but it is believed that a brief summary may be of interest to geologists.

Mars has a diameter of about 4200 miles and surface gravity 38 per cent of that of the earth. The visible features of the surface comprise: (1) the reddish "deserts" covering about 60 per cent of the area; (2) the so-called "seas", definitely not bodies of water, but gray to greenish areas that darken seasonally; (3) the white polar caps; (4) the controversial "canals" that seem to be related in nature to the "seas", since they darken and fade with them.

Spectroscopic study in the infra-red has established that the polar caps are H_2O snow (Kuiper, 1949, p. 337). However, the amount of water vapor in Mars' atmosphere is too little to detect spectroscopically and is probably less than .0015 of the moisture content above Mount Wilson (Dunham, 1949, p. 298). Carbon dioxide is present in slightly greater amount per square centimeter column than the terrestrial quantity (Kuiper, 1949, p. 335). Oxygen appears to be lacking, probably less than .0015 of the terrestrial amount (Dunham, 1949, p. 297). From polarization studies, and on the assumption that the light-scattering efficiency is equal to that of our air, it is calculated that the amount of atmosphere per square centimeter column is 22 per cent of ours, and the pressure at the ground (under reduced surface gravity) 83 millibars (Dollfus, 1951a). Measures of heat radiation indicate temperatures as high as 20°–30°C at noon in the Martian tropics, but night temperatures are as low as −85°C (Coblentz and Lampland, 1924; 1926; Coblentz, Lampland, and Menzel, 1927; Pettit and Nicholson, 1924).

The seasonal changes of color of the dark "seas" have often been attributed to growth of vegetation. However, these areas fail to show the strong reflection in the infra-red that characterizes our trees and grasses (Kuiper, 1949, p. 339). Lichens or mosses have been suggested as possible types that would satisfy the observations. Both the red and the dark regions show polarization of reflected light that matches closely the reflection from volcanic ash (Lyot, 1929; Dollfus and Cailleux, 1950). Kuiper (1949, p. 335) found the deserts showed a spectrum-reflection curve that matched a brownish felsite. More recently Dollfus (1951b) suggested the deserts are colored by finely divided limonite. It is quite certain that no appreciable quartzose sand or silt exists there (Dollfus and Cailleux, 1950).

During a series of observations in 1939 and 1941, the writer was repeatedly struck by the apparently systematic orientation of the dark "seas". The most conspicuous of them form a south tropical girdle about the planet. Within this zone several dark bands, alternating with light-colored ones, extend southeast to northwest (Pl. 1, figs. 1, 2). In the northern hemisphere, some of the strongest "canals" trend northeast to southwest. Several projections from the southern belt of "seas" cross the equator to the north, hooking around to the northeast as they do so, and terminating in more or less sharp points (Pl. 1, figs. 2, 3).

The alignments just described call to mind the trade winds. It is suggested that the banded pattern is due to deposits of dust, sand, or volcanic ash drifted by the winds. On occasion, yellowish clouds have been seen slowly changing position on the planet, and these can be satisfactorily interpreted only as great dust storms or ash clouds. The regularity of the banding may seem to be a point against the hypothesis, but it must be noted that Mars has no oceans or great mountain ranges to complicate its meteorology, and an extremely regular wind pattern is to be expected.

Mars' axial inclination is about equal to the earth's, but its orbit is much more eccentric. Northern summer occurs at aphelion and must be rather cool, and the winds must then be relatively weak. The southern summer at peri-

helion is surely characterized by stronger winds, and the main pattern of wind-blown material must be established at that time. When the Martian heat equator shifts far south, the northeast trades will cross south of the equator, be deflected to the left, and become northwest anti-trade winds. The phenomenon is similar to (but the inverse of) the southwest monsoon of India. In Figures 2 and 3 of Plate 1, the flow pattern can be seen crossing the equator and curving left. Figures 4, 5, and 6 of Plate 1 are wind diagrams for Figures 1 to 3, respectively.

The sharp points of the terminal "bays" of the dark areas now claim our attention. From the flow pattern, it is evident that *these points are sources of dark material that is drifted by the winds*. The only conceivable natural source of this kind is a volcano. Not only are volcanoes probably situated at the points of the "bays", but they also occur at a number of places on the deserts, and drifts of ash from some of them make streaks that have been mapped as "canals". Some of these are in the trade-wind belt, and others in the zone of the westerlies. The light-colored bands between the dark ones can be interpreted as drifts of the dust from the reddish deserts.

It has long been known that "canals" seem to enter the "seas" at the pointed bays. In terms of our hypothesis, some of these canals are trails of ash deposited when the feeble anti-trade winds of the northern summer were blowing. The apparent continuity of canals for 1000 miles or more is at least partly an illusion. The largest telescopes tend to show them as vague features or to resolve them into intricate detail (Antoniadi, 1930), though some observers have interpreted them as narrow lines (Lowell, 1908).

Not all canals can be accounted for by trai of ash. Some could well be wide fault zones comparable with such major tectonic feature as the Grenville front in the Canadian Shield or with the African rift valleys. Conceivably some fault zones could be loci of numerou minor volcanic vents whose ejecta might form apparently continuous lines across the deser areas.

The precise meaning of the seasonal change of color of the dark areas remains uncertain but it is probably related in some way to th arrival of the scanty moisture as it migrate from the north to the south polar cap and vic versa. The growth of some low form of vegeta tion on the ash deposits is not entirely ruled out but at least it must be viewed with skepticism It is suggested that the green color may be due to chlorite and epidote, resulting from al teration of ferromagnesian minerals by carbon dioxide and moisture, in the absence of oxygen

References Cited

Antoniadi, E. M., 1930, La Planete Mars: Hermann et Cie., Paris, p. 22–34.

Coblentz, W. W., and Lampland, C. O., 1924, Radiometric measurements on Mars: Pub. Astr. Soc. Pacific, v. 36, p. 272.

—— 1926, Radiometric measurements on the planet Mars, 1926: Pub. Astr. Soc. Pacific, v. 38, p. 355.

Coblentz, W. W., Lampland, C. O., and Meuel, D. H., 1927, Temperatures of Mars, 1926, as derived from the water-cell transmissions: Pub. Astr. Soc. Pacific, v. 39, p. 97.

Dollfus, A., 1951a, Détermination de la pression atmosphérique sur la planète Mars: Comptes Rendus (Paris), v. 232, p. 1066.

—— 1951b, La polarisation de la lumière renvoyée par les différentes régions de la surface de la planète Mars et son interprétation: Comptes Rendus (Paris), v. 233, p. 467.

Dollfus, A., and Cailleux, A., 1950, Étude polarimétrique de la lumière renvoyée par quelques

Plate 1. SKETCHES OF MARS AND WIND DIAGRAMS

Figures 1–3.—Sketches of Mars by the Author

From observations with 12-inch refracting telescope, University of Michigan, magnifying power approximately 300×. The south polar snow cap appears at the bottom of each figure.

Figure 1.—October 22, 1941, Martian longitude 170° central, showing south tropical belt with banded structure trending southeast.

Figure 2.—October 13, 1941, Martian longitude 270° central, showing south tropical banded structure trending southeast, and funnel-shaped "bays" pointing northeast in north tropical latitudes.

Figure 3.—July 7, 1939, Martian longitude 0° central, showing pointed "bays" north of equator and flow pattern curving left as it crosses equator. A high plateau (light area at lower right) causes a local disturbance of circulation.

Figures 4–6.—Wind Diagrams Corresponding to Sketches in Figures 1–3

The winds shown are those of summer in the southern hemisphere.

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sables et limons: Comptes Rendus (Paris), vol. 230, p. 1411.
Dunham, T., 1949, Spectroscopic observations of the planets at Mount Wilson *in* Kuiper, G. P., The atmospheres of the Earth and planets: Univ. Chicago Press, p. 286–303.
Kuiper, G. P., 1949, The atmospheres of the earth and planets: Univ. Chicago Press.
Lowell, P., 1908, Mars and its canals: Macmillan Co., New York.
Lyot, B., 1929, Recherches sur la polarisation de la lumière des planètes et de quelques substances terrestres: Annales de l'Obs. de Paris (sec. de Meudon), v. 8, pt. 1, p. 42, 117.
Pettit, E., and Nicholson, S. B., 1924, Radiation measures on the planet Mars: Pub. Astr. Soc. Pacific, v. 36, p. 269.

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